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Revision of Low Temperature Emission Standards for Petrol Vehicles

Christos Dardiotis
Giorgio Martini
Urbano Manfredi

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Contact information
Giorgio Martini
Address: Joint Research Centre, Via Enrico Fermi 2749, TP 441, 21027 Ispra (VA), Italy
E-mail: giorgio.martini@jrc.ec.europa.eu
Tel.: +39 0332 78 9293
Fax: +39 0332 78 5236

http://iet.jrc.ec.europa.eu/
http://www.jrc.ec.europa.eu/

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1 INTRODUCTION

The Commission Regulation (EC) No 692/2008 of 18 July 2008 [1] together with the Regulation (EC) No 715/2007 of the European Parliament and of the Council of 20 June 2007 [2] set the regulatory framework for type-approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6). In particular these regulations set the emission standards and the related implementing measures, divided into three different steps, that will enter into force between 2009 (Euro 5) and 2014 (Euro 6). However, the above mentioned Regulations leave open some issues regarding the Euro 5b and the Euro 6 emissions standards to be addressed and defined before the entry into force of these pieces of legislation.

As far as the low temperature emission test for gasoline vehicles is concerned the current emission limits, carried over from Euro 3 and Euro 4, are no longer appropriate for vehicles meeting the Euro 5 and Euro 6 emission standard.

2 BACKGROUND INFORMATION

This final report provides a picture of the low temperature emission performances (based on type approval data of Type VI test) of the current generation of gasoline vehicles. It also summarizes the main results of the experimental activity carried out at the Joint Research Centre (JRC) to investigate the behaviour at low temperature of Euro 5 passenger cars and provides useful data for the revision of the low temperature emission standard for gasoline vehicles. Moreover, the analysis includes also results of ethanol Flex Fuel Vehicles (FFV) in view of the extension of the low temperature test to this category of vehicles.

The test procedure and emission limits for the Type VI test (-7°C) date back to Euro 3/4 standards (Directive 98/69/EC [3]) and since then they have never been updated to be consistent with the Type I emission limits set for Euro 5 and Euro 6 standards.

It is worth reminding that Type I emission test (verifying the average exhaust emissions after a cold start) is carried out by driving the vehicle over the entire New European Driving Cycle (NEDC), while the Type VI test is limited to the urban part of the NEDC (i.e. the first 4 UDC15 elementary cycle), which is commonly indicated as Urban Driving Cycle (UDC). In addition over the low temperature test the dynamometer settings are adjusted for a 10% decrease of the coast-down time, meaning a corresponding increase of the resistance to progress (alternatively the coast down times measured at a temperature of -7°C should be used).

It was considered highly reasonable that, in order to comply with Euro 5 and Euro 6 emission limits (Type I test), the vehicle manufacturers would have to implement engine and after-treatment technical solutions which in turn would be beneficial also to the low temperature emissions.

Thus, the first phase of the activity carried out by JRC consisted in an analysis of the low temperature emissions measured in the type approval test of a range of the existing Euro 3/4/5a petrol vehicle/engine technologies. This analysis is complemented by low temperature emission tests on a number of Euro 5a petrol vehicles performed at the JRC Vehicle and Engine Emission Laboratories (VELA).

In the first part of this report an overview of the Carbon Monoxide (CO) and total Hydrocarbons (HC) emissions for Type VI test is provided. The vehicle emission data have been retrieved from the Kraftfahrt-Bundesamt (KBA), the Germany's Federal Motor Transport Authority [4]. The KBA regularly publishes fuel consumption and emission type approval values for new vehicles with national or EC type approval in order to be accessible to environmentally conscious citizens, in accordance with the EC-Directive 2003/4/EC [5].

In the second part, the regulated emissions of a number of Euro 5a mono fuel petrol vehicles currently available on the European market measured in Type I and Type VI tests are provided. The analysis includes also results of two flex fuel ethanol vehicles.

In theory in modern gasoline engines equipped with three way catalysts cold start CO and HC emissions may be explained by two main factors: First, the cold engine has to be run under richer conditions to avoid misfires due to condensation effects on the cylinder walls. Secondly and most important, the catalyst does not convert efficiently these emissions below its "light-off" temperature, which lies typically between 300 and 350°C. Since both effects depend on the temperature, it is obvious that the cold start emissions increase in the low ambient temperature test. Moreover, as already mentioned, the dynamometer settings are adjusted for a 10% decrease of the coast-down time, meaning a corresponding increase of the resistance to progress (alternatively the coast down times measured at a temperature of -7˚C could be used).

In the literature, an extensive survey of research carried out in the past concerning the cold start emissions is given in the report by André and Joumard in [6]. They collected data from various laboratories concerning cold start emission measurements over standardized and representative driving cycles. The aim of this study was to model the cold start impact on road vehicle emissions as functions of the pollutant and the vehicle type, using the existing data in Europe. Three models were developed, which can be applied at different geographic scales: at a macroscopic scale using road data indicators and temperature statistics, or at a microscopic scale for a vehicle and a trip. The third model replaced the Copert III cold start model within the tool Artemis.

The influence of ambient temperature on cold start gaseous emissions is investigated in the studies of Weilenmann et al. [7, 8]. They have measured – estimated the extra cold start gaseous emissions of gasoline and diesel vehicles. The vehicles' emission certification level ranges from old pre Euro 1 to Euro 4 and have been examined at three ambient temperatures (23, -7 and -20°C). They have also examined the dependence of cold start emissions on the driving conditions (e.g. urban, motorway) by testing the vehicles over various driving cycles. They conclude that for most pollutants the evolution of the cold start excess emissions is not linear with the ambient temperature. The majority of CO and HC emissions of gasoline vehicles are emitted during the cold start phase and increases with lower ambient temperatures. At -20°C the CO and HC emissions are up to 15 and 35 times higher than at 23°C respectively. In contrast, no evident trend can be detected for Oxides of Nitrogen (NO_x) emissions of the same vehicles. Cold start CO and HC emissions of diesel vehicles are significantly lower than those of gasoline ones. The cold start NO_x emissions of diesel vehicles depend on the Euro emission level. Vehicles up to Euro 2 emission level exhibit comparably low cold start NO_x emissions, with no clear dependence with ambient temperature for all the tested vehicles. The situation is different for Euro 4 diesel vehicles, which in contrast to the respective gasoline ones, there is an evident increase in NO_x emissions as the temperature decreases. The authors explain this increase due to the higher friction and consequently higher engine loads at low temperatures. It is speculated that increased NO_x emissions could be experienced at low ambient temperatures due to the decreased Exhaust Gas Recirculation (EGR) rate, in order to avoid water condensation in the EGR cooler and subsequently, corrosion of the cooled EGR components.

Laurikko [9, 10, 11] has been evaluating the cold start emission performance of new passenger cars since 1993. Each year a batch of 10 to 20 vehicles has been tested at -7°C, according to the European as well as to the US low ambient temperature test procedure. For gasoline vehicles he conclude that the average cold start CO emissions have decrease over 50% between Euro 2 and Euro 4 emission level cars, while total HC emissions have improved less (30%). Diesel vehicles have been also tested for their cold start emission performance. They emit almost one order of magnitude lower CO and HC emissions compared to gasoline ones and typically the worst performing diesel cars are close to the best performing gasoline cars.

In the studies of Bielaczyc and Merkisz [12, 13] gasoline vehicles model year 1994-1996 were tested over the NEDC and United States (US) Federal Test Procedure (FTP-75) driving cycles at various ambient temperatures from -15°C to 22°C. The gaseous CO, HC and NO_x emission performance is discussed. CO and HC emissions increase proportionally to the decrease of the ambient temperature. Moreover, the time of the cycle during which increased concentrations are experienced increases from 195 s at 22°C (first quarter of UDC) to 780 s at -15°C (over the whole UDC). On the contrary, in case of NO_x emissions, no obvious tendency was identified as the test temperature decreases.

Particle emissions of Euro 3 gasoline and diesel vehicles at low ambient temperatures are investigated in the study of Mathis et al. [14]. They performed measurements of particle number, active surface area, number size distribution and mass size distribution of port and direct injection gasoline vehicles, and diesel vehicles with and without Diesel Particulate Filter (DPF) at an ambient temperature ranging from 23 to -20°C. The results depend on the engine and exhaust after-treatment technology. While for gasoline vehicles and diesel with DPF particle concentrations increased remarkably during cold starts when decreasing ambient temperature, particle emissions were hardly affected in the case of diesel vehicles without DPF.

The investigation of the effect on emissions of engine stop time has been presented in Favez et al. [15]. In this study the influence of exhaust emissions with stop times shorter than 12 hours (i.e. 0.5, 1, 2 and 4 hours) is investigated. Emissions of recent Euro 4 vehicles are compared with the emissions assessed in the framework of a similar campaign carried out 10 years before with Euro 1 vehicles. They conclude that for medium stop times of 0.5 to 4 hours the average relative cold start extra emissions of recent Euro 4 vehicles are well below the respective ones of 10-year-old Euro 1 vehicles. Such investigation is not examined in this report, as the preconditioning and the soak method before the low temperature test are determined by the legislation.

3 SCOPE AND OBJECTIVES OF THIS STUDY

JRC has carried out a study to support a possible revision of the low temperature emission standards (Type VI test) for gasoline Euro 5 and Euro 6 vehicles. The main objectives of this study were:

- Analyze the type approval data to investigate the CO and total HC low temperature (-7°C) emissions of the existing Euro 3/4/5a vehicles.
- Measure low temperature emissions from a range of Euro 5a mono fuel petrol vehicle/engine technologies, testing various vehicles at the JRC VELA Laboratory. Two flex fuel ethanol vehicles (one Euro 4 and one late technology Euro 5) were also included in the measurement matrix, which were tested running in two fuels, with low and high ethanol content.

4 ANALYSIS OF TYPE APPROVAL DATA

4.1 INTRODUCTION

The data published by the Kraftfahrt-Bundesamt contains type approval emissions of vehicles and engines. The low temperature emissions of positive ignition passenger cars have been measured in the Type VI test in accordance with EC-Directive 70/220/EEC [16] and following amendments (see also Regulation (EC) No 715/2007 [2] or ECE Regulation 83 [17]).

Mono-fuel, Bi-fuel and Flex-fuel petrol ethanol vehicles are subjected to the low ambient temperature emission test. Mono-fuel Liquefied Petroleum Gas (LPG) and Compressed Natural Gas (NG/biomethane or CNG) vehicles are not subjected to the Type VI test of the above Regulation. Bi-fuel gas vehicles that can run on petrol and on either LPG/CNG/biomethane or Hydrogen should be tested at the Type VI test on petrol only. Flex-fuel ethanol vehicles can run on petrol or on a mixture of petrol and ethanol up to an 85% ethanol blend (E85). These vehicles should be tested at low temperature using both reference fuels E5 and E75, for vehicles certified as Euro 5a. FFV vehicles up to Euro 4 emission standard were not subjected to Type VI type approval test.

Table 1 presents the requirements for type approval of petrol vehicles at low temperature (Type VI test) depending on the vehicle technology.

Table 1 – Type approval of vehicles with positive ignition engines (including hybrids) at low temperature test (Type VI).

	Mono-fuel				**Bi-fuel**			**Flex-fuel**
Reference fuel	Petrol (E5)	LPG	NG/ Biomethane	Hydrogen	Petrol (E5)	Petrol (E5)	Petrol (E5)	Petrol (E5)
					LPG	NG/ Biomethane	Hydrogen	Ethanol (E75)
Low temperature emissions (Type 6 test)	Yes	No	No	No	Yes (petrol only)	Yes (petrol only)	Yes (petrol only)	Yes (both fuels)

Table 2 provides the emission limits for CO and total HC in the low temperature test (-7°C) that is limited to the urban part of the NEDC. The emission values are available for three vehicle categories: The passenger vehicles (M category) and the commercial (N_1 and N_2 category). In this study only the passenger cars belonging to the M category and the passenger vehicles certified as N_1 category - class I due to their weight, are examined. These two categories (M and N_1 class I) have the same limits for the CO mass (15 g/km) and for the total HC mass (1.8 g/km).

Table 2 – Euro 5a emission limits for CO and total HC tailpipe emissions after a cold start low ambient temperature test (-7°C).

Vehicle category	Class	Mass of CO [g/km]	Mass of HC [g/km]
M	-	15	1.8
N1	I	15	1.8
	II	24	2.7
	III	30	3.2
N2	-	30	3.2

4.2 ANALYSIS OF THE DATA REFERRED TO CAR MODELS

The type approval data published by KBA were analysed to investigate the evolution of the low temperature emission performances of petrol vehicles.

In the KBA data set the type approval low temperature emissions were available for a number of models that were divided into seven categories depending on the engine technology. Table 3 shows the different categories, the total number of vehicles in each category and the number of vehicles belonging to a given category that comply respectively to Euro 3, 4 and 5a emission standards. The first row provides the total number of petrol vehicles of a given emission standard for which the type approval data was available.

Within each category/technology, the number of vehicles complying with a given emission standard (Euro 3, 4 or 5a) was in some case not sufficient for a statistical analysis. For example, in the case of Direct Injection petrol vehicles (G-DI) only the Euro 4 and Euro 5a sub-categories were taken into consideration since only one model fell in the Euro 3 sub-category. This study is based on the current available KBA data of March 2009, explaining why the majority of the vehicles comply with the Euro 4 emission standards.

The sub-categories taken into consideration for the analysis are underlined and in bold in Table 3.

The number of cars falling in the last three categories (Petrol or Electrical – RG, Petrol or Ethanol – FFV and Petrol Wankel Rotary – WG) was not sufficient for a statistical analysis. However, for these vehicles the highest type approval emission value measured in the low temperature test was 8.1 g/km for CO and 1.37 g/km for total HC. These values are, as expected, within the low temperature emission limits and correspond to the 54% and 76.1% respectively of the current CO and total HC limits of 15 g/km and 1.8 g/km.

Table 3 – Petrol vehicle categories and number of vehicles.

Category name	Engine Technology	Number of vehicles		
		Euro 3	Euro 4	Euro 5a
Total vehicles	Petrol		**3540**	
		83	**3072**	385
PFI	Petrol Port Fuel Injection		**2710**	
		76	**2466**	168
G-DI	Petrol Direct Injection		**749**	
		1	**537**	**211**
CNG	Petrol or Compressed Natural Gas		**47**	
		2	**40**	5
LPG	Petrol or Liquefied Petroleum Gas		**21**	
		4	**17**	0
RG	Petrol or Electrical		7	
		0	6	1
FFV	Petrol or Ethanol		4	
		0	4	0
WG	Petrol Wankel Rotary		2	
		0	2	0

Figure 1 shows the CO and total HC emission values of the examined vehicle categories in X-Y scatter chart format. The vehicles complying with the low temperature emission limits for passenger cars provided in Table 2 fall inside the box (the lines correspond to the emission limits). The majority of the vehicles belong to the petrol PFI category, as described above. It is worthwhile to mention that some vehicles of this category exceed the total HC limits. However the vehicles exceeding the limits represent only the 0.4% of the total PFI vehicles. All the vehicles that exceed the HC limits are Euro 4 and one Euro 5a.

The LPG and CNG vehicles have been tested in the low temperature test on petrol fuel only, consequently, they do not differ much from their respective mono-fuel versions. Also the FFV vehicles have been tested when running on petrol only, since all the examined vehicles have been certified as Euro 4.

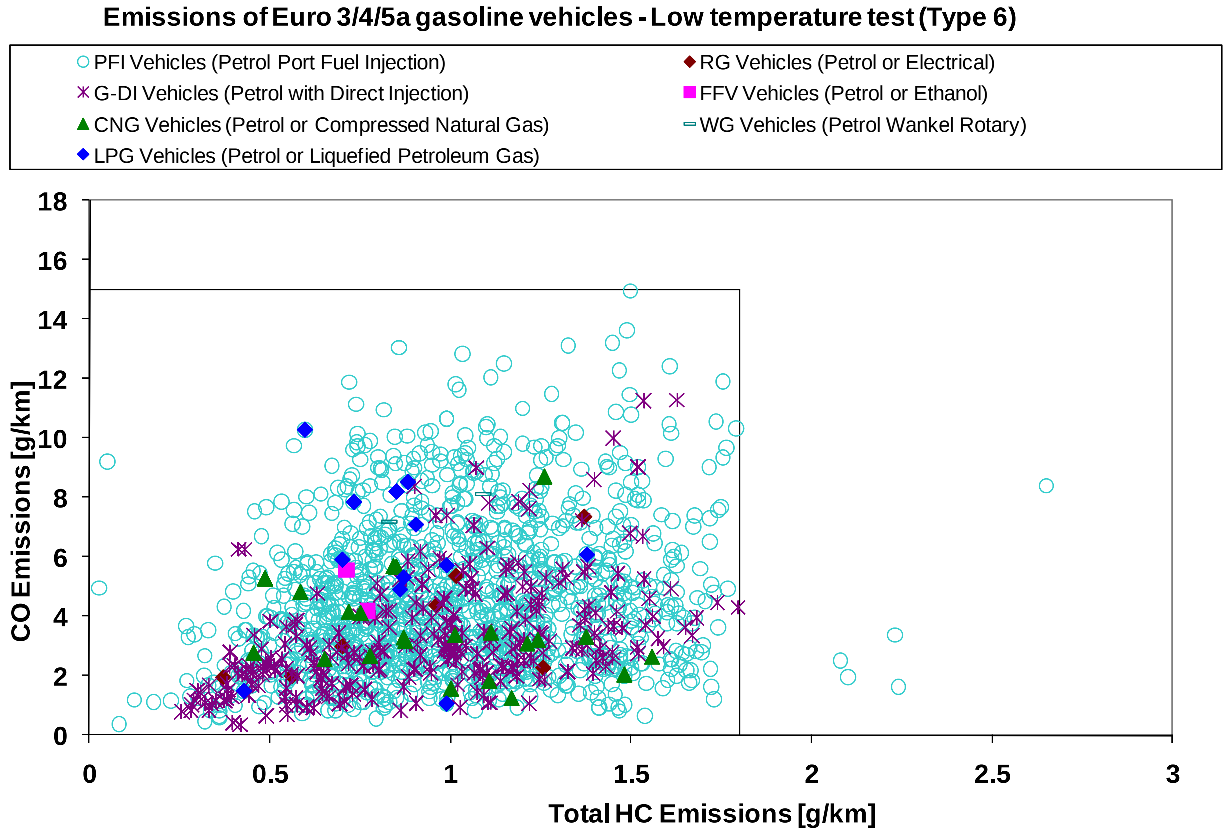
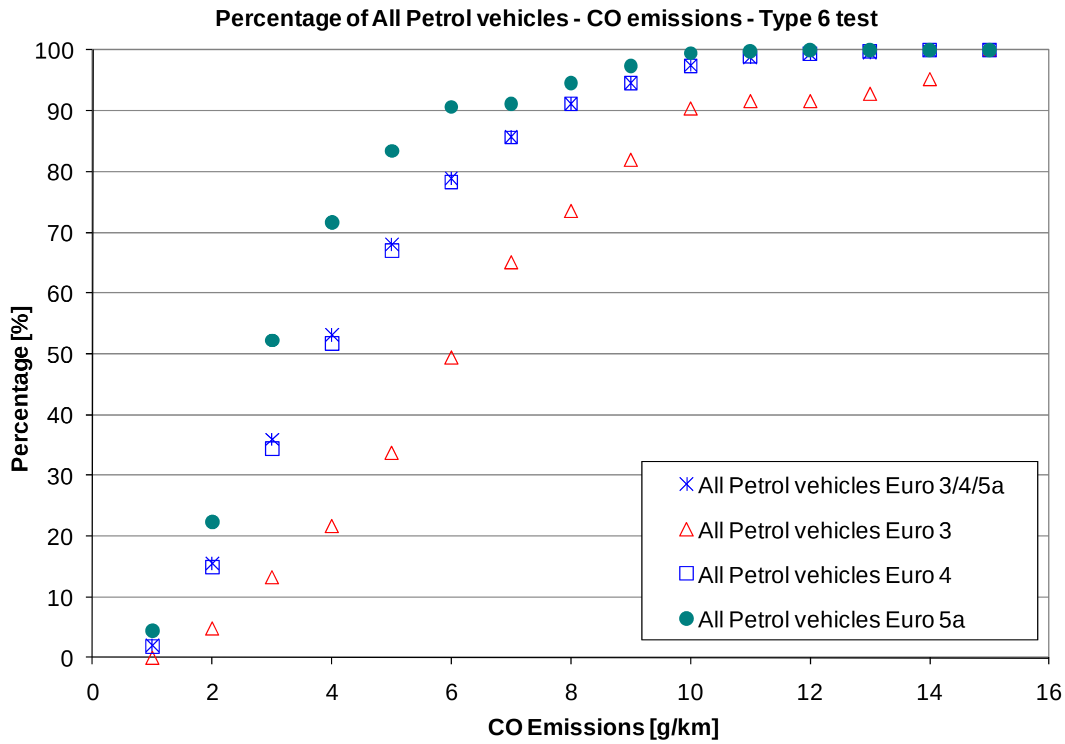


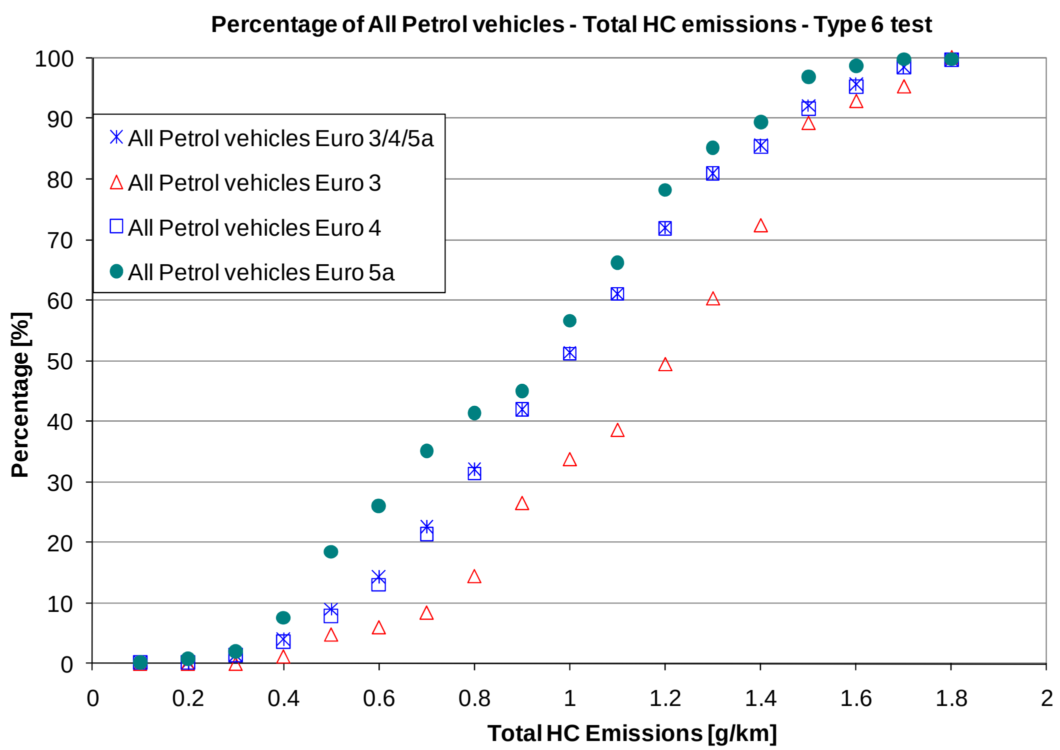
Figure 1 – CO and total HC emissions of the examined vehicle categories in Type VI test (the box represents the low temperature emission limits).

In order to verify if the type approval data shows any specific pattern as a function of engine technology, the percentage of vehicles having emissions measured in the Type VI test lower than given values of CO and total HC emissions has been calculated. Figure 2 shows the computed results for all the petrol vehicles analyzed and for each emission level (Euro 3/4/5a) respectively for CO (a) and total HC (b).

Since the majority (87%) of the vehicles in the KBA data set complies with the Euro 4 limits, the values calculated for the Euro 4 vehicles result to be very close to the respective values referred to all the vehicles (Euro 3/4/5a).



(a)



(b)

Figure 2 – Percentage of all Petrol vehicles having emissions measured in the Type VI test lower than given values (X axis) of (a) CO and (b) total HC emissions.

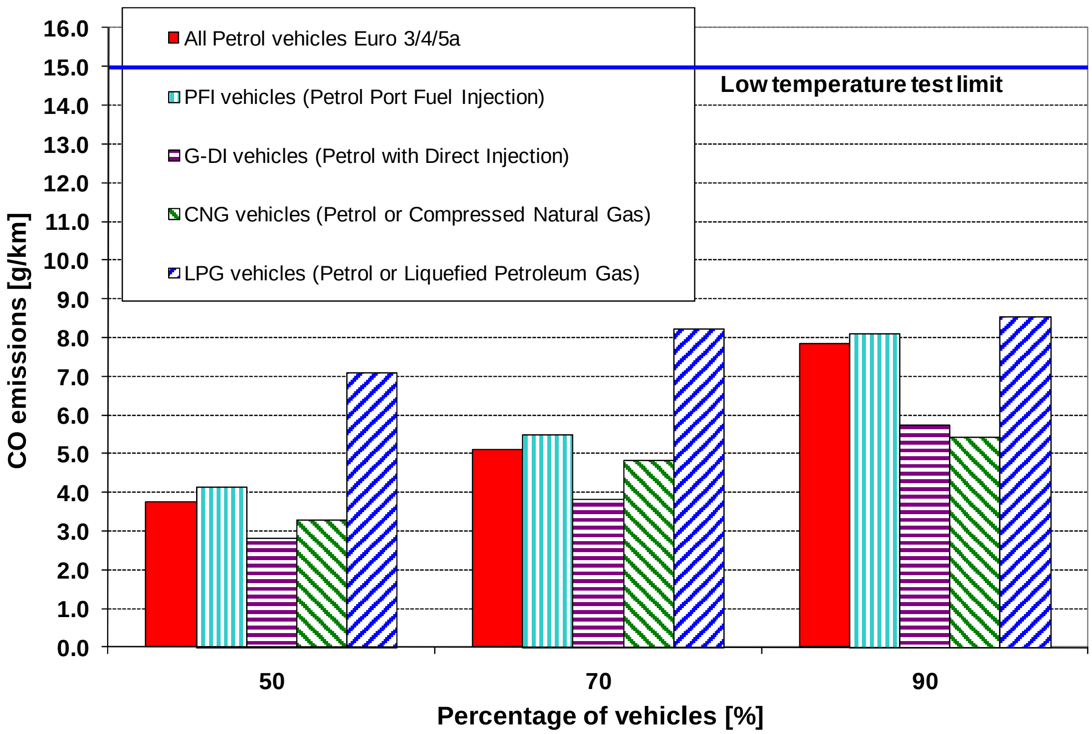
The two plots show the improvement of the vehicle performance as the emission technology level changes. For instance, the percentage of the vehicles which emit less than 6 g/km of CO in the low temperature test increases by 58% (from 49% to 78%) when moving from Euro 3 to Euro 4 emission level. The increase is instead only 16% (from 78% to 90.5%) moving from Euro 4 to Euro 5a emission level. The same trend is valid for total HC. For instance, the percentage of vehicles having HC emissions lower than 1.2 g/km increases by 45% (from 49% to 72%) from Euro 3 to Euro 4 emission level, and by 9% (from 72% to 78%) from Euro 4 to Euro 5a. This can be explained considering the evolution of the emission standards for the Type I test. The limits for HC and CO were considerably reduced with the introduction of the Euro 4 (from 0.2 to 0.1 g/km for total HC and from 2.3 to 1 g/km for CO) while no further reduction was considered necessary for the Euro 5a standards. Therefore, in order to comply with the Euro 4 emission standards the manufacturers had to improve a lot the performances of the exhaust after-treatment devices of the vehicles, especially to cut the cold start emissions which represent the vast majority of the total emissions in the Type I test. On the contrary, no improvement was required to comply with the Euro 5a standards, as far as CO and total HC are concerned.

In order to quantify the differences among the various vehicle categories and their sub-categories, the CO and total HC emission levels corresponding to the 50th, 70th and 90th percentile of all the petrol vehicles and of the vehicles falling in each category have been calculated. The results are shown in Figure 3. The low temperature emission limits are indicated with solid lines (15 and 1.8 g/km for CO and total HC respectively). The above mentioned values have been calculated for each pollutant separately. This means that a vehicle having CO emissions within the 50th percentile (i.e. below 3.8 g/km for all petrol vehicles) does not necessarily has total HC emissions within the 50th percentile (below 0.98 g/km).

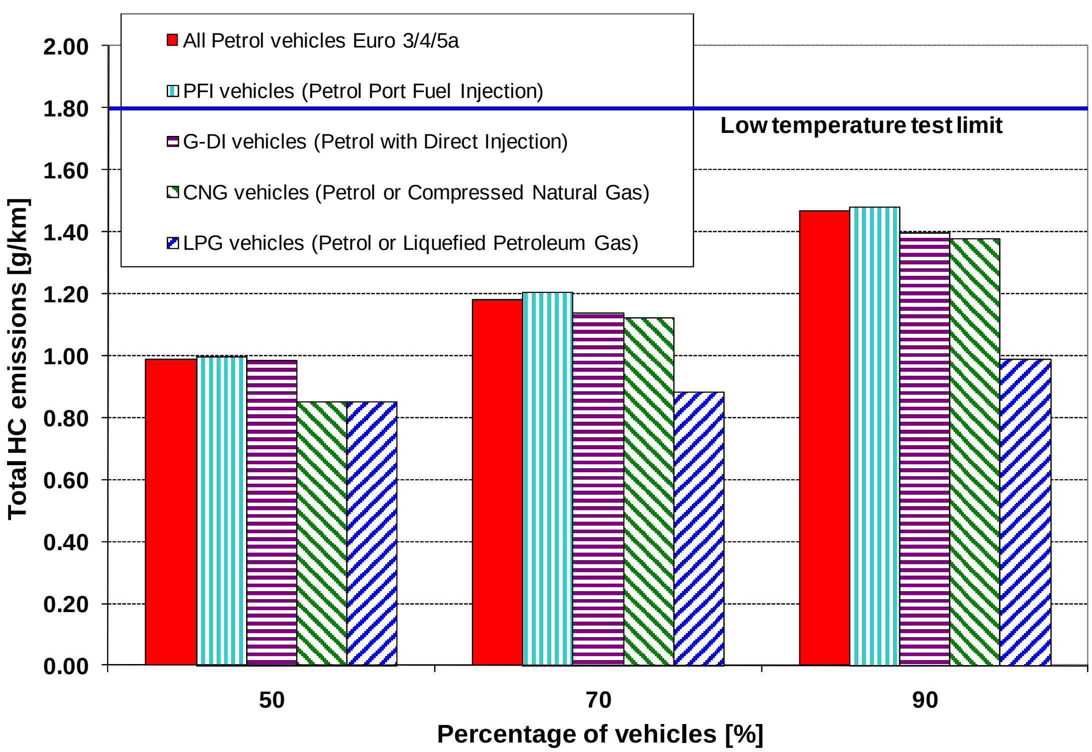
From the bar chart it appears that the petrol vehicles with direct injection systems (G-DI) have in general lower CO emissions than the other categories. The fact that the number of analyzed vehicles falling in the G-DI category is the second highest is of course reflected in the values referred to all the petrol vehicles which, as a consequence, result lower than the values calculated for the vehicles with port fuel injection system (PFI).

The LPG category of vehicles comprises 47 vehicles, accounting only for 1.3% of the total. They emit more CO and less total HC compared to the other categories of vehicles.

Table 4 shows the calculated values for each vehicle sub-category.



(a)



(b)

Figure 3 – (a) CO and (b) Total HC emission levels measured in the Type VI test corresponding to the 50th, 70th and 90th percentile of all the petrol vehicles analyzed and their technology categories.

Looking at the data referred to all the vehicles, it can be noticed that the improvement for the low temperature CO emissions is quite impressive. The CO emission value corresponding to the 90th percentile of total Euro 3 vehicles was 9.8 g/km while for Euro 5a vehicles the 90th percentile decreases to 6.7 g/km. For total HC emissions the difference between Euro 3 and Euro 5a vehicles is smaller: 90% of Euro 5a vehicles emit less than 1.41 g/km while the 90th percentile value for Euro 3 was 1.51 g/km.

Table 4 – CO and total HC emission values corresponding to the 50th, 70th and 90th percentile of petrol vehicles and sub-categories – Type VI test. All the values are expressed in g/km (UDC cycle).

Vehicle category	50% Percentile		70% Percentile		90% Percentile	
	CO	HC	CO	HC	CO	HC
All petrol	**3.8**	**0.99**	**5.1**	**1.18**	**7.9**	**1.47**
All petrol Euro 3	6.2	1.20	7.7	1.37	9.8	1.51
All petrol Euro 4	3.8	0.99	5.2	1.18	7.8	1.47
All petrol Euro 5a	32.8	0.94	3.9	1.14	6.7	1.41
All PFI	**4.1**	**1.00**	**5.5**	**1.21**	**8.1**	**1.48**
PFI Euro 3	6.0	1.23	7.4	1.40	10.0	1.53
PFI Euro 4	4.1	0.99	5.5	1.20	8.0	1.48
PFI Euro 5a	3.2	1.02	4.1	1.16	5.6	1.43
All G-DI	**2.8**	**0.98**	**3.8**	**1.14**	**5.7**	**1.40**
G-DI Euro 4	2.9	01.00	3.8	1.11	5.0	1.40
G-DI Euro 5a	2.7	0.74	3.7	1.07	5.9	1.37
All CNG	**3.3**	**0.85**	**4.8**	**1.12**	**5.4**	**1.38**
CNG Euro 4	3.2	0.86	4.8	1.13	5.3	1.39
All LPG	**7.1**	**0.85**	**8.2**	**0.88**	**8.5**	**0.99**
LPG Euro 4	5.9	0.90	7.9	0.90	9.2	1.00

As far as the vehicles with direct injection engines (G-DI) are concerned, the differences between Euro 4 and 5a sub-categories result smaller compared to PFI cars.

This small difference could be partly due to the fact that in the KBA data set the number of direct injection vehicles complying with the Euro 4 standards is much higher (71.8% of the total car number) than the vehicles complying with the Euro 5a standards (28.2% of the total).

Nevertheless, from the available data it could be concluded that the Euro 5a models with direct injection engines do not show significant progress compared to Euro 4 models. However, Euro 4 G-DI appears to have better emission performances than Euro 4 PFI. In fact 90% of them emit less than 5.0 g/km of CO and 1.40 g/km of total HC, while the 90th percentile for the Euro 4 PFI cars emit less than 8.0 g/km and 1.48 g/km for CO and total HC respectively.

4.3 ANALYSIS OF THE DATA REFERRED TO ENGINES

In this section the type approval data are analyzed on the basis of the engine type rather than on the basis of the car model in order to check whether the emission patterns discussed in the previous chapter changes significantly. In the type approval data set there are in fact several different car models with the same manufacturer's engine code and, in addition, with identical low temperature emissions. In order to avoid multiple counting of engines with the same technology, in this analysis only the vehicles equipped with different engines (i.e. different engine code) have been considered, while all the other models equipped with the same engine have been excluded. In a case where the engine code is different and the emissions are the same, no models have been excluded, because, according to the manufacturer, the engine type is different.

Table 5 presents an example where different models are equipped with the same type of engine, but have different power and vehicle design (here the "touring" means "station wagon" vehicle design). The emissions measured in the low temperature test are exactly the same and this implies that the engine is identical. Therefore, for the analysis described in this section, only the first model has been taken into consideration while the other three have been excluded.

Table 5 – Example of models from the same manufacturer, with the same type of engine and emissions in Type VI test.

Manufacturer	Model	Engine code	Power [KW]	Emission level	Emissions in the low temperature test [g/km]	
					CO	HC
BMW	318i	N43B20A	100	Euro 4	1.04	0.339
BMW	318i	N43B20A	105	Euro 4	1.04	0.339
BMW	318i TOURING	N43B20A	100	Euro 4	1.04	0.339
BMW	318i TOURING	N43B20A	105	Euro 4	1.04	0.339

The same engine type can be shared also by models from different manufacturers. However, in general, the different manufacturers belong to the same group like VW (Audi-VW-Seat-Skoda), PSA (Peugeot-Citroen), Renault-Nissan Alliance, Hyundai-Kia Group. Table 6 presents an example where different car brands from the same group use the same engine. These models have also different vehicle design, but the low temperature test emissions are identical, according to the KBA data. Also in this case only the first model has been kept while all the other models have been excluded.

Table 6 – Example of models from different manufacturers, with the same type of engine and emissions in Type VI test.

Manufacturer	Model	Engine code	Emission level	Emissions at low temperature test [g/km]	
				CO	HC
AUDI	A3	BSE	Euro 4	3.837	0.801
AUDI	A3 CABRIO	BSE	Euro 4	3.837	0.801
AUDI	A3 SPORTB	BSE	Euro 4	3.837	0.801
SKODA	OCTAVIA	BSE	Euro 4	3.837	0.801
SKODA	OCTAVIA COMBI	BSE	Euro 4	3.837	0.801

A third case which is worthwhile to mention is when there are models using the same engine code, with the same low temperature emissions, but with different emission limits for Type I test. Table 7 shows a case where there are models with the same engine and low temperature emissions, but that comply with different Euro standards. In this case the emissions of the Type I test are different, but the emissions of the Type VI test are identical, according to the obtained data. Consequently, none of the below vehicles has been excluded.

Table 7 – Example of models with the same type of engine and emissions in Type VI test, comply with different Euro standards.

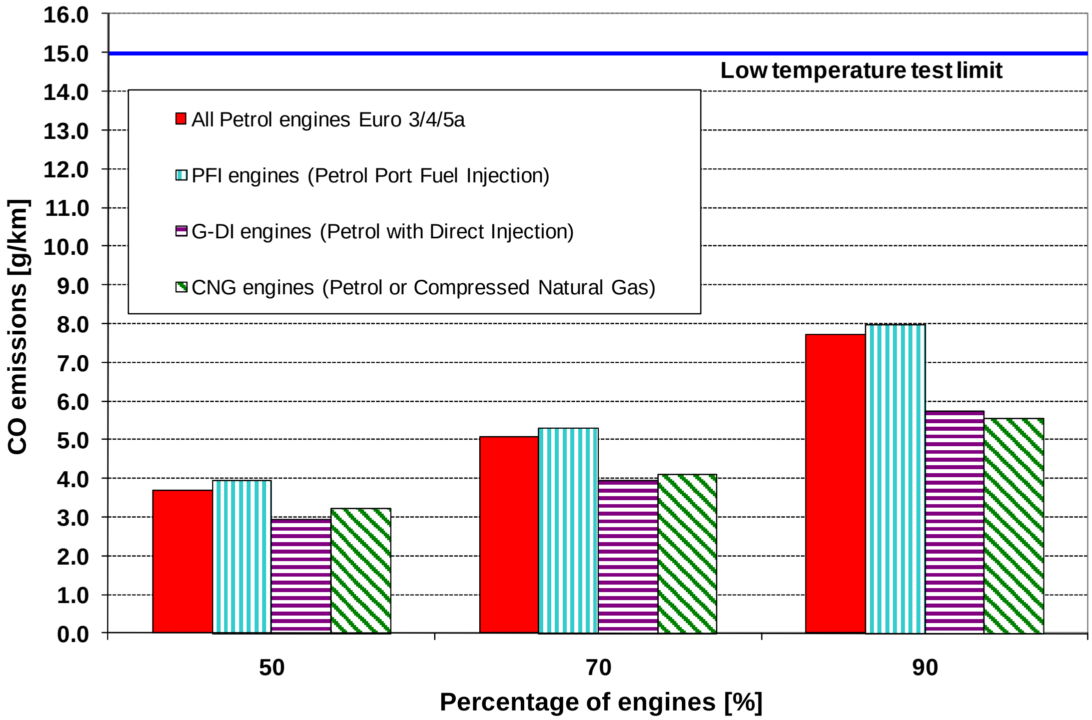
Manufacturer	Model	Engine code	Emission level	Emissions at low temperature test [g/km]	
				CO	HC
PORSCHE	BOXTER	MA120	Euro 4	4.083	1.22
PORSCHE	BOXTER	MA120	Euro 5a	4.083	1.22

Like in the previous section, the examined vehicles/engines have been divided in seven categories, depending on their technology. Table 8 shows the various categories, the number of vehicles/engines in each category and the number of vehicles/engines complying with the Euro 3, 4 and 5a emission standards. The categories and sub-categories referred to each engine technology are the same as in Table 3, apart from the LPG engines since, after having excluded the models equipped with identical engines, the number of the engines is not sufficient to carry out a statistical analysis. In any case, 100% of all the engines contributing to the LPG, RG (Petrol or Electrical), FFV (Petrol or Ethanol) and WG (Petrol Wankel) categories, comply with the low temperature emission limits, with maximum emission values of 10.3 g/km and 1.38 g/km for the CO and total HC respectively.

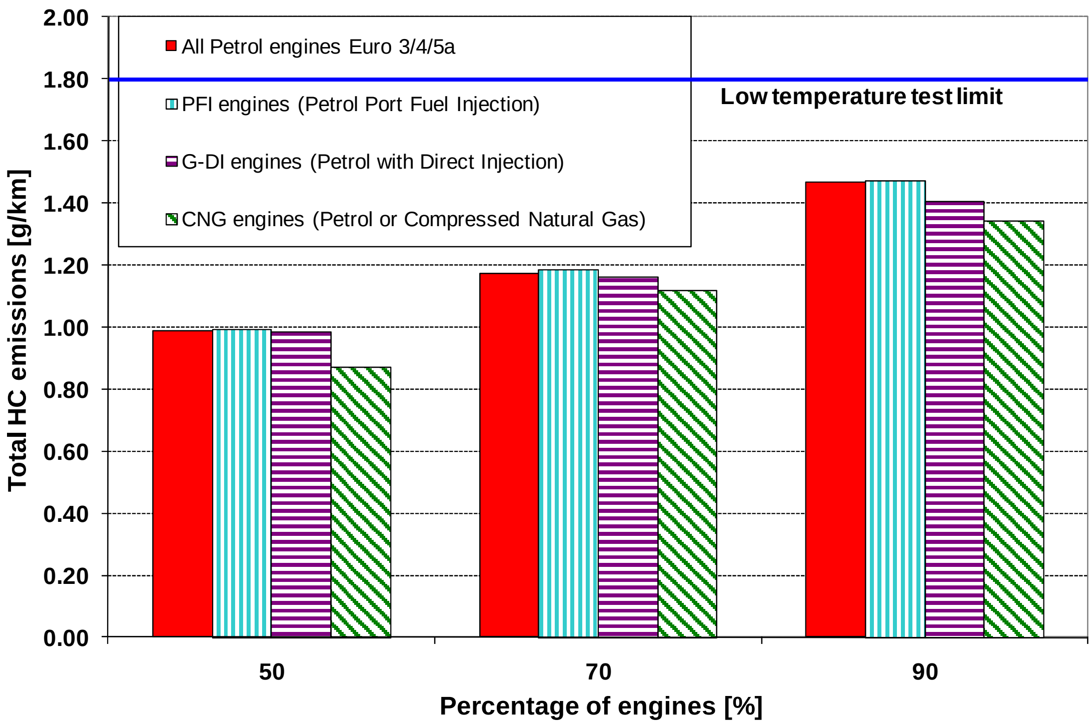
Table 8 – Petrol engine categories and number of engines.

Category name	Engine Technology	Number of engines		
		Euro 3	Euro 4	Euro 5a
Total engines	Petrol		**1832**	
		55	**1550**	**227**
PFI	Petrol Port Fuel Injection		**1456**	
		51	**1284**	**121**
G-DI	Petrol Direct injection		**330**	
		1	**227**	**102**
CNG	Petrol or Compressed Natural Gas		**24**	
		2	**19**	3
LPG	Petrol or Liquefied Petroleum Gas		10	
		1	9	0
RG	Petrol or Electrical		7	
		0	6	1
FFV	Petrol or Ethanol		3	
		0	3	0
WG	Petrol Wankel Rotary		2	
		0	2	0

Figure 4 shows the low temperature CO and total HC emission values corresponding to the 50^{th}, 70^{th} and 90^{th} percentile of all the petrol engines and their basic categories. Although almost half of the vehicles included in the analysis discussed in the previous section have been excluded, the conclusions are quite similar and the general picture does not change significantly. The direct injection engines (G-DI) and the engines with either petrol or compressed natural gas (CNG) seem to emit lower emissions compared to the petrol port fuel injection engines (PFI).



(a)



(b)

Figure 4 – (a) CO and (b) Total HC emission levels measured in the Type VI test corresponding to the 50th, 70th and 90th percentile of Petrol engines and their basic categories.

Table 9 provides the emission values corresponding to the 50th, 70th and 90th percentile for each engine category and sub-category. The differences with Table 4 are small. 90% of Euro 5a engines emit less that 5.6 g/km CO and 1.43 g/km total HC in the low temperature test, while the respective values for the 70th percentile are 3.8 g/km and 1.16 g/km.

Table 9 – CO and HC emission values measured in the Type VI test corresponding to the 50th, 70th and 90th percentile of Petrol engines and their sub-categories. All the values are expressed in g/km.

Engine category	50%		70%		90%	
	CO	HC	CO	HC	CO	HC
All petrol	**3.7**	**0.99**	**5.1**	**1.17**	**7.7**	**1.47**
All petrol Euro 3	5.5	1.22	7.0	1.40	9.7	1.53
All petrol Euro 4	3.8	0.98	5.1	1.17	7.8	1.47
All petrol Euro 5a	3.0	1.01	3.8	1.16	5.6	1.43
All PFI	**4.0**	**0.99**	**5.3**	**1.18**	**8.0**	**1.47**
PFI Euro 3	5.6	1.24	7.0	1.41	9.8	1.54
PFI Euro 4	4.0	0.98	5.4	1.17	8.0	1.48
PFI Euro 5a	3.2	1.04	3.8	1.16	5.0	1.43
All G-DI	**2.9**	**0.99**	**4.0**	**1.16**	**5.7**	**1.40**
G-DI Euro 4	2.9	0.99	4.0	1.16	5.6	1.40
G-DI Euro 5a	2.9	0.98	3.8	1.16	5.9	1.42
All CNG	**3.2**	**0.87**	**4.1**	**1.12**	**5.5**	**1.34**
CNG Euro 4	3.2	0.87	3.4	1.15	5.3	1.40

5 TESTS CARRIED OUT AT THE JRC

In this part of the report, the low temperature emissions from a range of Euro 5a gasoline vehicle/engine technologies tested at the VELA laboratory at JRC are presented.

5.1 TEST VEHICLES

Six vehicles with Port Fuel Injection (PFI) engine and four with Gasoline Direct Injection (G-DI) engine were selected for the experimental campaign. Table 10 provides the main characteristics of the tested vehicles. Vehicles 1 to 8 are gasoline mono fuel, while Vehicles 9 and 10 are ethanol Flex Fuel Vehicles (FFV). All the vehicles featured rather low mileage, apart from Vehicle 6, which had accumulated about 42000 km.

Table 10 – Vehicles' data and specifications.

Vehicle	Emission Standard	Injection system	Engine	Mileage [km]	Manufacturer's CO_2 emission [g/km]
Vehicle 1	5a	G-DI	1995cc 105kW	8353	143
Vehicle 2	5a	PFI	1242cc 44kW	1909	128
Vehicle 3	5a	PFI	1595cc 75kW	7285	166
Vehicle 4	5a	PFI	1242cc 51kW	13699	119
Vehicle 5	5a	PFI	1490cc 82kW	35	139
Vehicle 6	5a	PFI	1368cc 57kW	42146	124
Vehicle 7	5a	G-DI	1984cc 132kW	12461	167
Vehicle 8	4	G-DI	4608cc 280kW	28641	261
Vehicle 9 (FFV)	5a	G-DI	1984cc 132kW	1411	154
Vehicle 10 (FFV)	4	PFI	1798cc 92kW	11772	177

All mono-fuel vehicles were complying with Euro 5a emission standards, apart from Vehicle 8 (Euro 4). Flex fuel ethanol vehicles can run on petrol or on a mixture of petrol and ethanol up to an 85% ethanol blend (E85). Vehicle 9 was a late-technology turbocharged direct injection gasoline vehicle, complying with the Euro 5a emission standards. On the contrary, Vehicle 10 was a PFI one, complying with Euro 4 emission standards, representing the previous generation of the flex fuel ethanol vehicles. Vehicle 10 as Euro 4 FFV was subjected to Type VI test for type approval when running on petrol only.

5.2 FUELS

Vehicles 1 to 8 were tested with petrol fuel without ethanol content (E0), while flex fuel vehicles 9 and 10 were tested at 22°C for Type I test with the gasoline fuels E5 and E85 with 5% and 85% ethanol content respectively. At -7°C for the purpose of Type VI test flex fuel vehicles were tested again with petrol fuel E5 mentioned above and with E75 petrol fuel of 75% ethanol content.

5.3 INSTRUMENTATION DETAILS

The emission measurements were carried out in a test cell equipped with a chassis dynamometer and a Constant Volume Sampling (CVS) system. The measurements were performed according to the current legislative procedures for type approval. However for both the tests at 22 °C and -7 °C the NEDC cycle was used. The bag gaseous emissions are therefore available for the whole cycle as well as for the urban and extra-urban part of the driving cycle (UDC and EUDC respectively). In addition, second by second data of emission concentrations in the raw exhaust were also recorded.

A Horiba MEXA-7400HTR-LE analyzer bench was employed for bag gaseous emission measurement (Oxides of Nitrogen (NO_x), total Hydrocarbons (HC), Carbon Monoxide (CO) and Carbon Dioxide (CO_2)). In addition, second by second data of emission concentrations in the raw exhaust were also recorded. The real time traces of Oxygen (O_2), CO_2, CO and HC provided the means for the calculation of lambda.

The measurements were conducted in the VELA 2 test cell of JRC vehicle emission laboratory. The CVS is equipped with four critical orifices that allow to select the most appropriate flow rate from a minimum of 3.1 m^3/min to a maximum of 30.8 m^3/min. For the examined vehicles a CVS flow rate of 6 m^3/min has been employed for all the tested vehicles, apart from Vehicle 8 (8.8 m^3/min).

The roller bench of the chassis dynamometer is a single roller type manufactured by MAHA GmbH, with the following characteristics:

- Diameter: 48”
- Inertia range: 454 – 45000 kg
- Maximum speed: 200 km/h

As far as the dynamometer’s settings are concerned, the dynamometer load prescribed by the legislation was used since the road coast down data were not available for these vehicles.

In the low temperature tests, the dynamometer loads were increased by 10% as required by the legislation (as an alternative the road coast down data measured at -7°C can be used).

The use of the dynamometer loads prescribed by the legislation instead of the road coast down data may affect significantly the emission results since the rolling resistance provided by the Regulation 83 in general underestimates the resistance to progress of the vehicle at low speed and overestimates it at high speed. This may result in higher CO_2 and NO_x emissions especially over the extra-urban part of the cycle while CO and HC are usually affected to a lesser extent. In fact CO and HC are mostly emitted during the cold start on which the chassis dynamometer settings have a limited influence considering also the low speeds and the relatively soft accelerations involved in the first second of the NEDC cycle.

The vehicle to vehicle variability should be taken into consideration when evaluating the measured results. As a consequence, the emission values presented in the following sections may be different from those measured by the manufacturer at the type approval; nevertheless the trends and the general picture should not change significantly.

5.4 DRIVING CYCLE

All vehicles were tested under the standard New European Driving Cycle shown in Figure 5. The cycle has been used in Europe for certification of light-duty vehicles since 2000 and consists of the Urban Driving Cycle (UDC), which includes four repetitions of the Elementary Urban Cycle, and the Extra Urban Driving Cycle (EUDC).

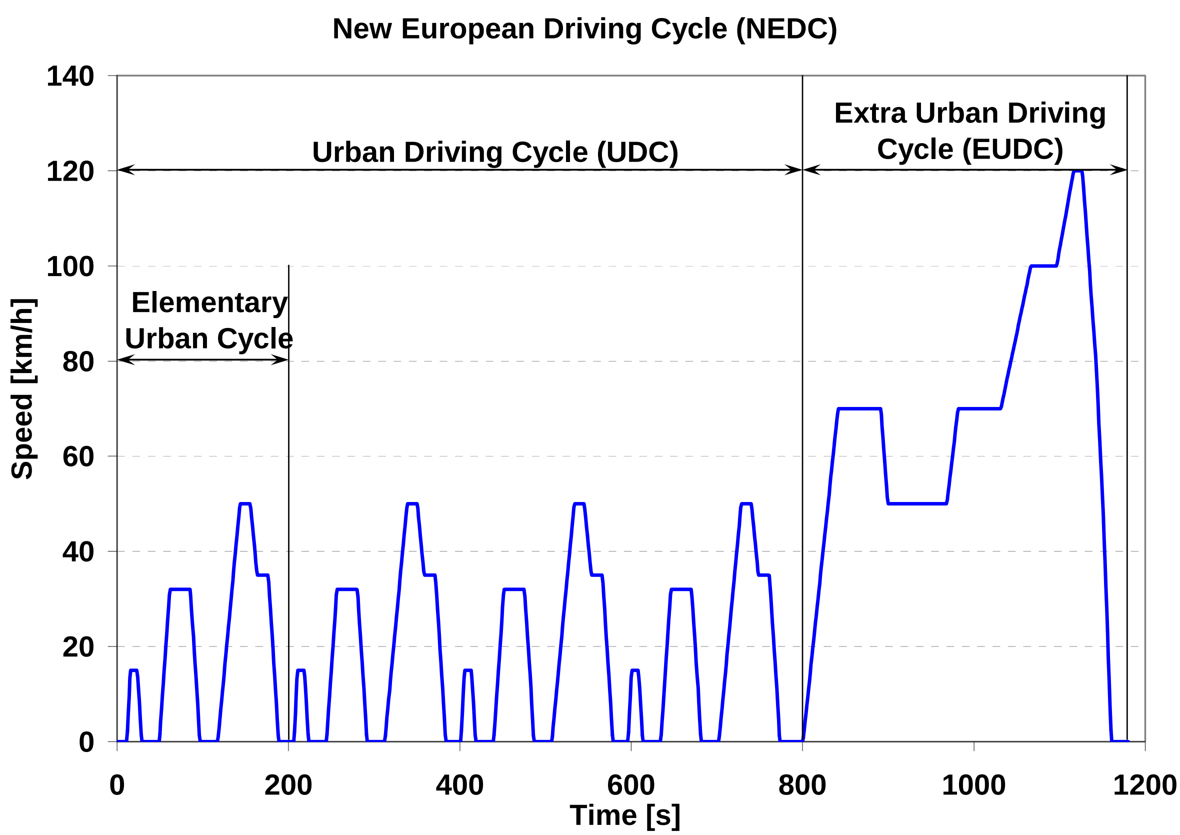


Figure 5 – New European Driving Cycle (NEDC) and its two phases: Urban (UDC) and Extra-Urban (EUDC).

5.5 TEST RESULTS

In this chapter the emission results both for Type I and Type VI tests of each vehicle are provided. All data shown is the average of at least two repetitions, apart from two cases where only one valid measurement was available and will be mentioned.

VEHICLE 1

Table 11 provides the average bag emission values and fuel consumption for the first vehicle investigated that was equipped with a direct injection engine running lean in certain operating conditions For this vehicle at 22°C only one value for gaseous emission was available, due to a problem to the analyzers.

Three different emission values are given: The emissions measured over the NEDC cycle (at 22°C) and the emissions measured over the urban part of the cycle (UDC) at 22 and -7°C. The data referred to the NEDC at 22°C and to the UDC cycle at -7°C represent respectively the results of the Type I and Type VI tests. Although the legislation of the low temperature emissions has set limits only for CO and total HC, the NO_x, and CO_2 emissions have been measured as well and are provided for all the tested vehicles.

The values given in parentheses refer to the type approval values (where available). The CO, CO_2, NO_x and fuel consumption values measured at the JRC were higher compared to the type approval values. Total HC emissions were almost the same in both cases (test at JRC and type approval data). In addition to the natural variability of emissions even among cars of the same model, one of the reasons explaining the higher measured values is for sure the use of different dynamometer load settings as explained above.

Table 11 – Measured gaseous emissions and fuel consumption for the Vehicle 1 over the NEDC (22°C) and UDC (22°C & -7°C) driving cycles (in parentheses the type approval data from KBA).

VEHICLE 1				
Emissions	**Unit**	**NEDC 22°C**	**UDC 22°C**	**UDC -7°C**
HC	g/km	0.043 (0.044)	0.098	0.249 (0.281)
CO	g/km	0.312 (0.120)	0.601	1.357 (0.84)
NO_x	g/km	0.050 (0.026)	0.046	0.035
CO_2	g/km	163.4 (143)	205.1 (186)	259.3
Fuel Consumption	l/100km	7.0 (6.2)	8.8 (8)	11.2

Figure 6 shows the bag emission values for total HC, CO, CO_2 and NO_x at 22 and -7°C measured over the NEDC, UDC and EUDC driving cycles. In the plots the Euro 5a limits for CO, HC and NO_x (1, 0.1 and 0.06 g/km respectively) for Type I test (Category M – Passenger

Vehicles) over the NEDC cycle are indicated by a red solid line. The low temperature test limits for CO and HC (15 and 1.8 g/km respectively) by a blue solid line. The manufacturer's CO_2 emission value (143 g/km) over the NEDC cycle is indicated in the respective chart by a green solid line. The scale is the same for all the tested vehicles for a better comparison. The error bars represent the maximum and minimum measured value.

The vehicle complies with the Type I test emission limits (test at 22°C, NEDC), as it was expected. In the test conducted at low ambient temperature (-7°C), HC, CO and NO_x over the NEDC cycle increased by 126%, 93% and 16.9% respectively. Even with this increase the measured CO and total HC emissions over the UDC cycle were almost one order of magnitude below the legislative limits of 15 g/km and 1.8 g/km respectively. The increase in CO_2 emissions over the NEDC was 14.2%.

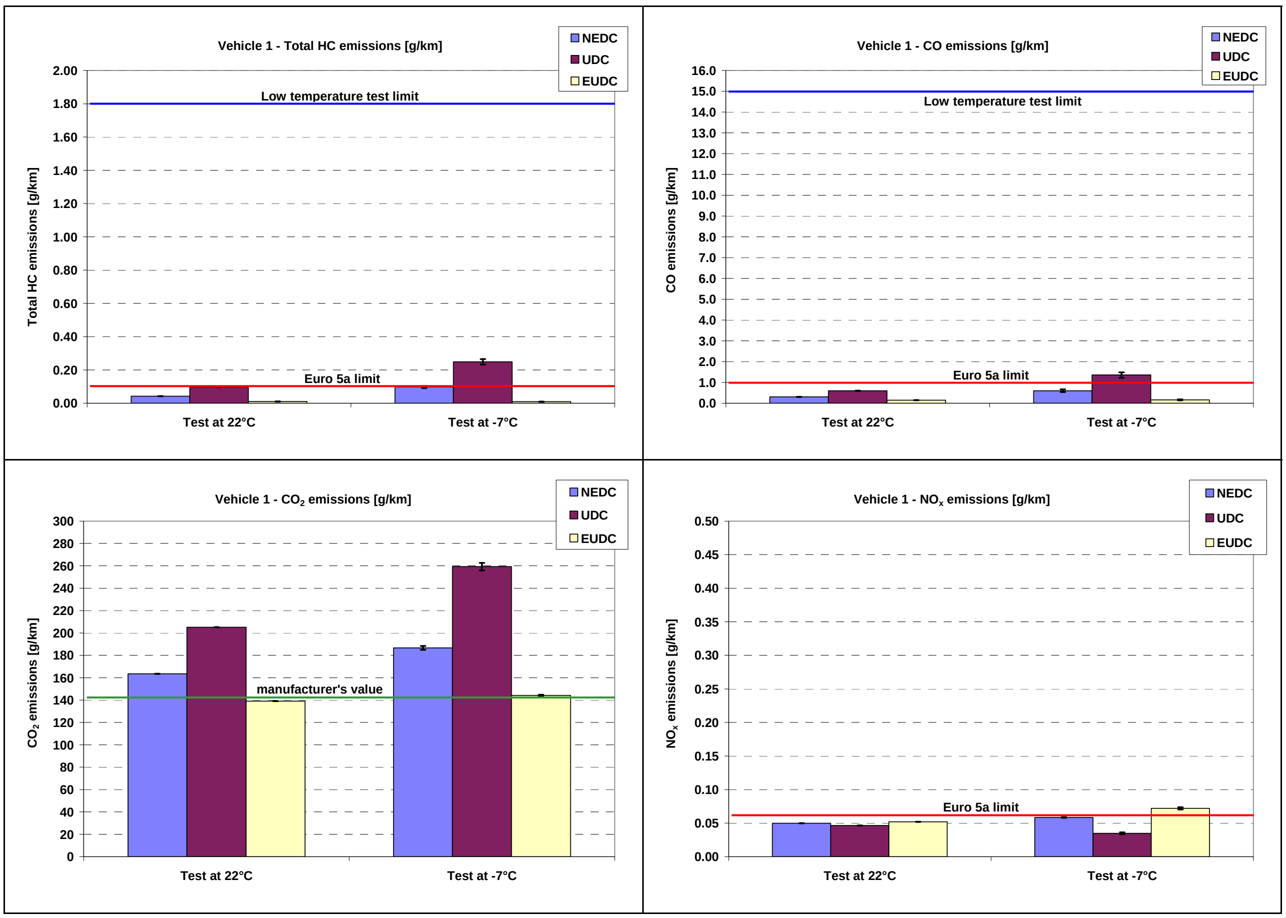
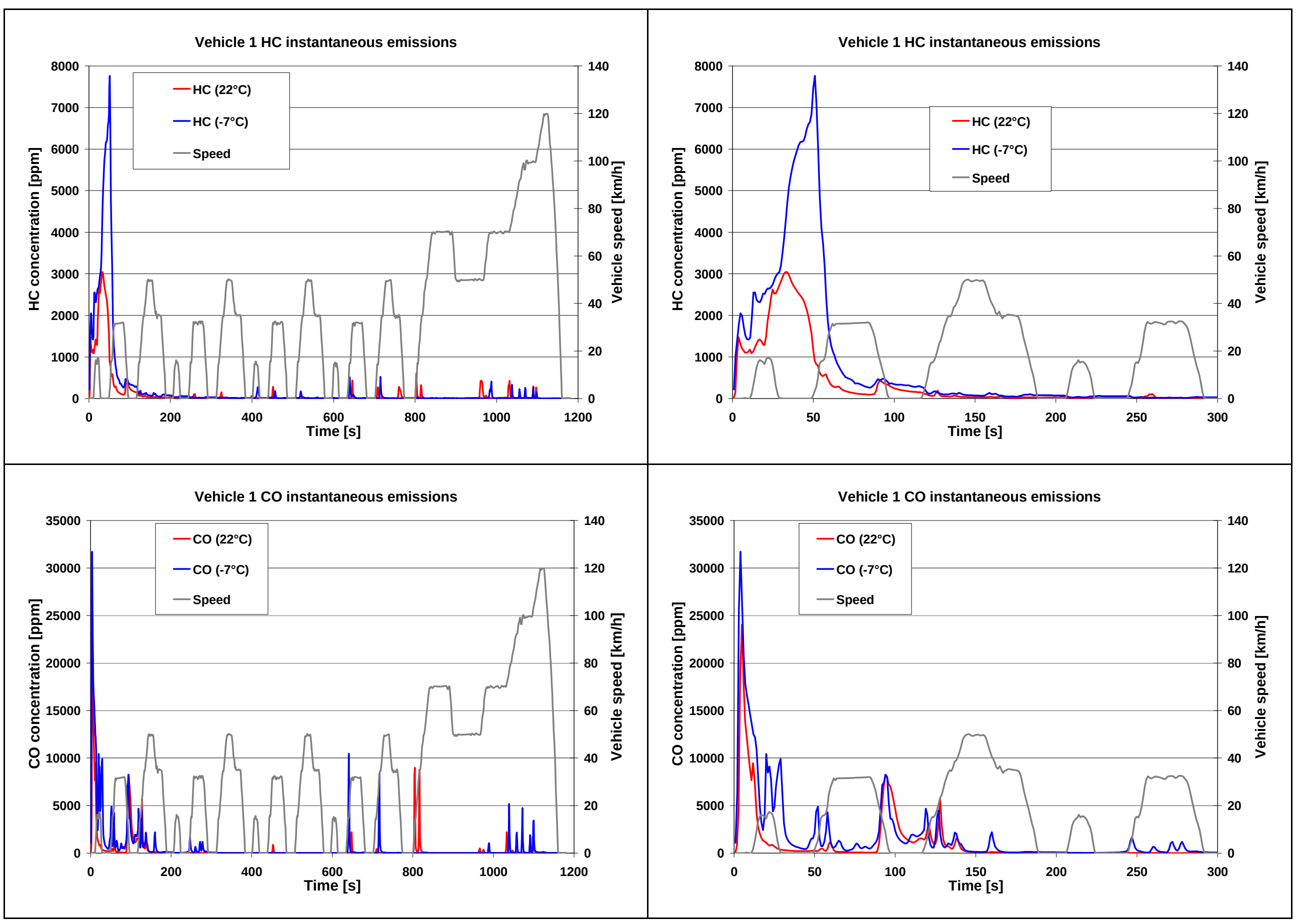


Figure 6 – Vehicle 1: Total HC, CO, CO_2 and NO_x bag emission values measured at 22°C and -7°C over the NEDC, UDC and EUDC driving cycles.

Figure 7 shows the gaseous instantaneous emissions and the calculated lambda value over the whole NEDC. A detail of the first 300 s of the cycle for both ambient temperatures (22 and -7˚C) is also provided. During the first seconds the catalyst did not work at its full efficiency and therefore this was the most critical part of the cycle as far as CO and HC emissions are concerned. The majority of the total HC and CO emissions were in fact generated during the first seconds as it is shown in the following Figure 8. At -7°C the concentration peaks of CO and especially HC almost doubled over the first part of the cycle. The main reason is the fact that catalyst's warming up was slower at -7°C, as this is an external temperature dependent phenomenon. After the catalyst's warming up was over and the fully efficiency was reached the emissions at the two temperatures were almost the same as demonstrated by the emission profiles recorded between 300 s and 800 s, (until the end of the urban part of the cycle). However, in the -7°C test an increase of CO emissions was detected also during the extra-urban part of the cycle, probably due to increased chassis dynamometer loads.

The instantaneous NO_x emissions and the lambda value over the two NEDC cycles are also shown in Figure 7. NO_x concentration was low over the urban part of the cycle due to the relatively low engine load. Some peaks of NO_x appeared during accelerations especially at 22°C. NO_x emissions increased over the extra-urban part of the cycle and especially after the instant 950 s, when the vehicle accelerated for the last part of the cycle. The calculated lambda value pattern shows that the engine, which used a direct fuel injection system, ran lean during the majority of the cycle. During the first seconds of the cycle the engine ran in stoichiometric mode (lambda 1) enriching the fuel-air mixture for rapid warming up of the catalyst's substrate. This specific operation of the engine may be a temperature dependent phenomenon, since at -7°C the stoichiometric operation lasted longer. In this case, the lean operation started after 300 s, while at 22°C it started after the first 150 s of the cycle. The stoichiometric combustion was instead predominant during the last part of EUDC cycle, when the vehicle accelerated up to the maximum speed and the engine load increased.



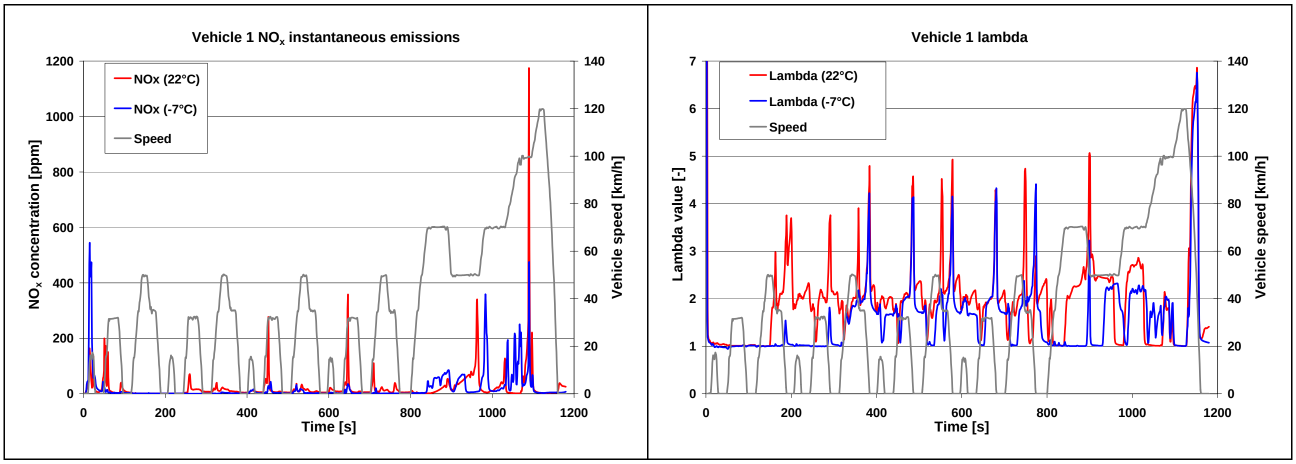


Figure 7 – Vehicle 1: Total HC, CO and NO_x instantaneous emissions and lambda value over the NEDC driving cycle at 22°C and -7°C.

Figure 8 shows the cumulative gaseous emissions of the same vehicle over the NEDC cycle at the two different test temperatures. This kind of chart is very helpful to investigate the different evolution of each pollutant over the whole cycle at low and regular ambient temperature. In this case the CO and HC evolution was quite similar. There was a rapid increase of pollutant mass during the first 100-150 s, until the warming up of the catalyst completed. Then, until the end of the urban part of the cycle, the accumulated mass was almost constant. Over the extra-urban part of the cycle the CO and HC mass increased again due to the increased engine load. As it has already discussed in Figure 7, the cumulative emissions of these two pollutants measured over the NEDC cycle at -7°C almost doubled compared to the respective emissions at 22°C.

Figure 8 shows also the cumulative mass of NO_x emissions that exhibit a different evolution compared to CO and HC. Most of the NO_x mass was emitted over the extra-urban part of the cycle, where the engine load increased. Moreover, NO_x emissions seem to be quite independent on the ambient temperature. As it has already mentioned in Figure 6 the mean increase of the NO_x mass measured in bags was 17%.

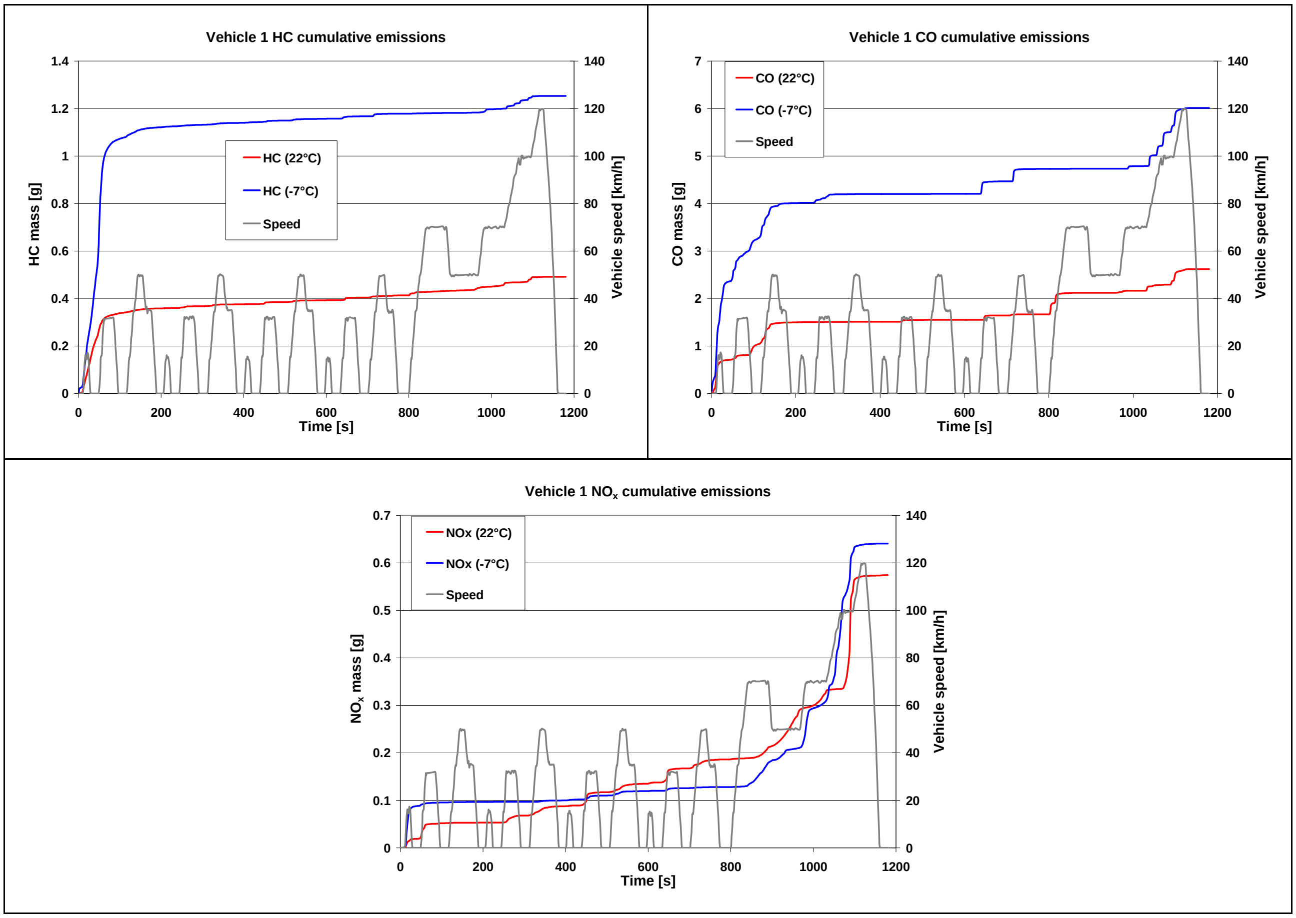


Figure 8 – Vehicle 1: Total HC, CO and NO_x cumulative mass emissions over the NEDC driving cycle at 22°C and -7°C.

Vehicle 1 was also tested for particulate emissions both in terms of mass (Particulate Matter – PM) and Particle Number (PN). Figure 9 shows the PM and PN emission results in both the ambient and low temperature tests. The PM was measured over the NEDC and is expressed in mg/km, while the PN is shown over the NEDC, UDC and EUDC cycles and is expressed in particles(#)/km (logarithmic scale). Moreover, the Euro 5b limits for PM and PN (4.5 mg/km and 6.0×10^{11} #/km respectively) are indicated with red solid line. The PM limit is valid for gasoline vehicles with direct injection engine, like in the case of Vehicle 1, while the abovementioned PN limit is applied to diesel vehicles only. The total PM mass emissions were not affected by the temperature of the test since the measured PM mass was almost the same at both the test temperatures (22°C and -7°C). The PM emissions were in both cases around 3.3 mg/km, complying with the legislative limit of 4.5 mg/km.

The PN emission value of Vehicle 1 measured in the 22°C test over the NEDC cycle was 1.38×10^{13} #/km. The value measured over the NEDC at -7°C was 1.64×10^{13} #/km, while over the UDC cycle was 2.30×10^{13} #/km. All these values are two orders of magnitude higher than the Euro 5b/Euro 6 limit of 6.0×10^{11} #/km applicable for diesel vehicles. The high PN emissions were due to the combustion mode of the direct injection engine which runs lean most of the time over the NEDC. Like for PM, PN emissions were not affected by the test temperature.

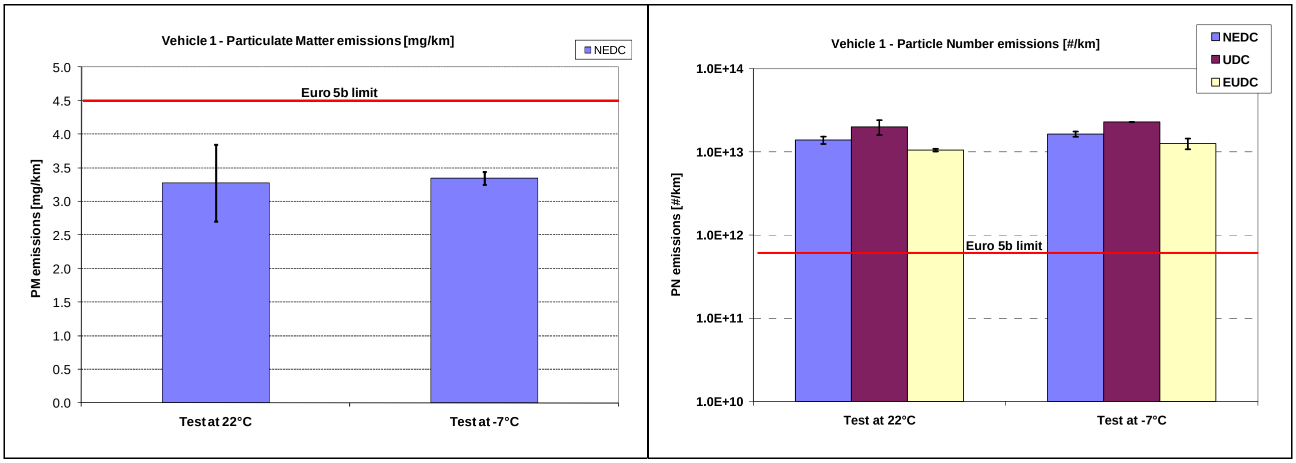


Figure 9 – Vehicle 1: PM emission measurement over the NEDC and PN emission values over the NEDC, UDC and EUDC driving cycles at 22°C and -7°C.

Figure 10 shows the instantaneous PN rate (in terms of #/s) over the NEDC cycle for both the test temperatures. The particles were emitted continuously over the cycle. The PN peaks were recorded in different time instants in the Type I and Type VI tests, probably due to the different engine strategy as it has already shown in Figure 7. The cumulative PN emissions over the NEDC cycle for both the temperatures are shown in Figure 10. As the vehicle ran mainly in lean mode over the NEDC cycle, the PN were emitted over the whole duration of the cycle, which caused an almost linear increase of emitted particles. For these two specific measurements the particle number emissions were very close over the NEDC ($1.52x10^{13}$ #/km).

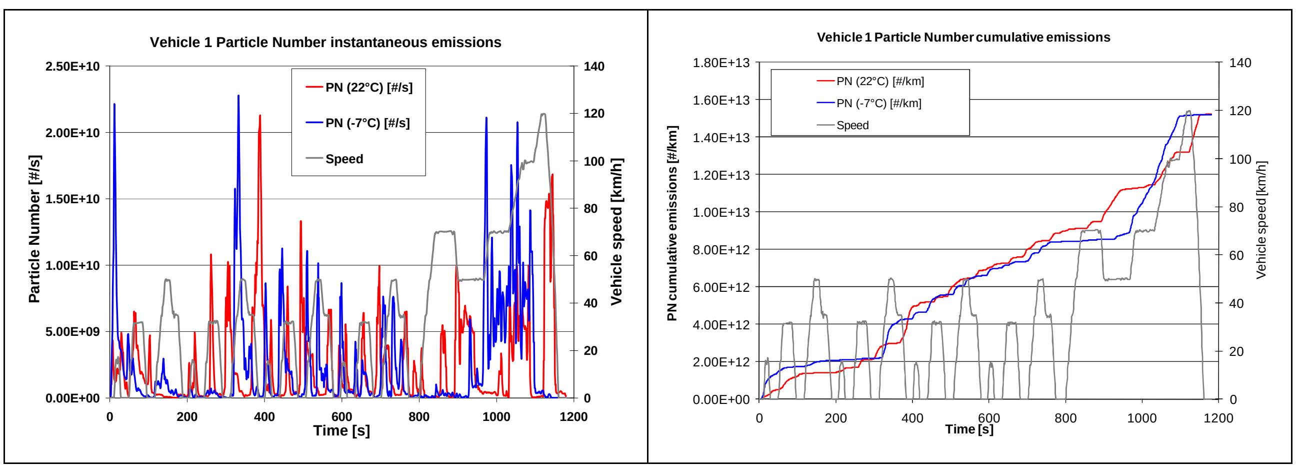


Figure 10 – Vehicle 1: Instantaneous PN rate and cumulative values over the NEDC driving cycle at 22°C and -7°C.

VEHICLE 2

Table 12 provides the mean bag emission values and the fuel consumption over the NEDC (22°C) and the UDC (22 & -7°C) cycles of Vehicle 2. As it was expected, the vehicle complies with the legislative limits in both ambient (NEDC 22°C) and low temperature tests (UDC -7°C). In this case CO and HC gaseous emissions were affected to a greater extent by the low ambient temperature than the previous vehicle. The type approval data for Type VI test (-7°C) were not available for this specific model, as the KBA data set was published in March 2009 before the introduction of Vehicle 2 into the European market. However, the type approval CO, HC and NO_x for Type I test (22°C - NEDC), and CO_2, fuel consumption values (NEDC and UDC)are given in parentheses.

Table 12 – Measured gaseous emissions and fuel consumption for the Vehicle 2 over the NEDC (22°C) and UDC (22°C & -7°C) driving cycles (in parentheses the type approval data of Type I test at 22°C).

VEHICLE 2				
Emissions	**Unit**	**NEDC 22°C**	**UDC 22°C**	**UDC -7°C**
HC	g/km	0.071 (0.051)	0.163	0.600
CO	g/km	0.358 (0.519)	0.738	8.336
NO_x	g/km	0.028 (0.028)	0.041	0.033
CO_2	g/km	143.3 (128)	181.5 (173)	219.8
Fuel Consumption	l/100km	6.2 (5.4)	7.8 (7.3)	10.1

Figure 11 shows the gaseous emission values in bar chart format for both the test temperatures over the NEDC, UDC and EUDC driving cycles. For this vehicle HC and CO emissions measured over the NEDC cycle at -7°C increased by 3.2 and 8.8 times respectively compared to the test carried out at 22°C. Despite this big difference, the emission values over the UDC cycle were 0.6 g/km and 8.34 g/km for total HC and CO respectively, which are well below the current legislative limits of 1.8 g/km and 15 g/km. The measured CO_2 value at 22°C was 143.3 g/km, while the value declared by the manufacturer was 128 g/km.

NO_x emissions at -7°C increased by 17% over the whole cycle (NEDC), possibly due to the increased dynamometer load settings.

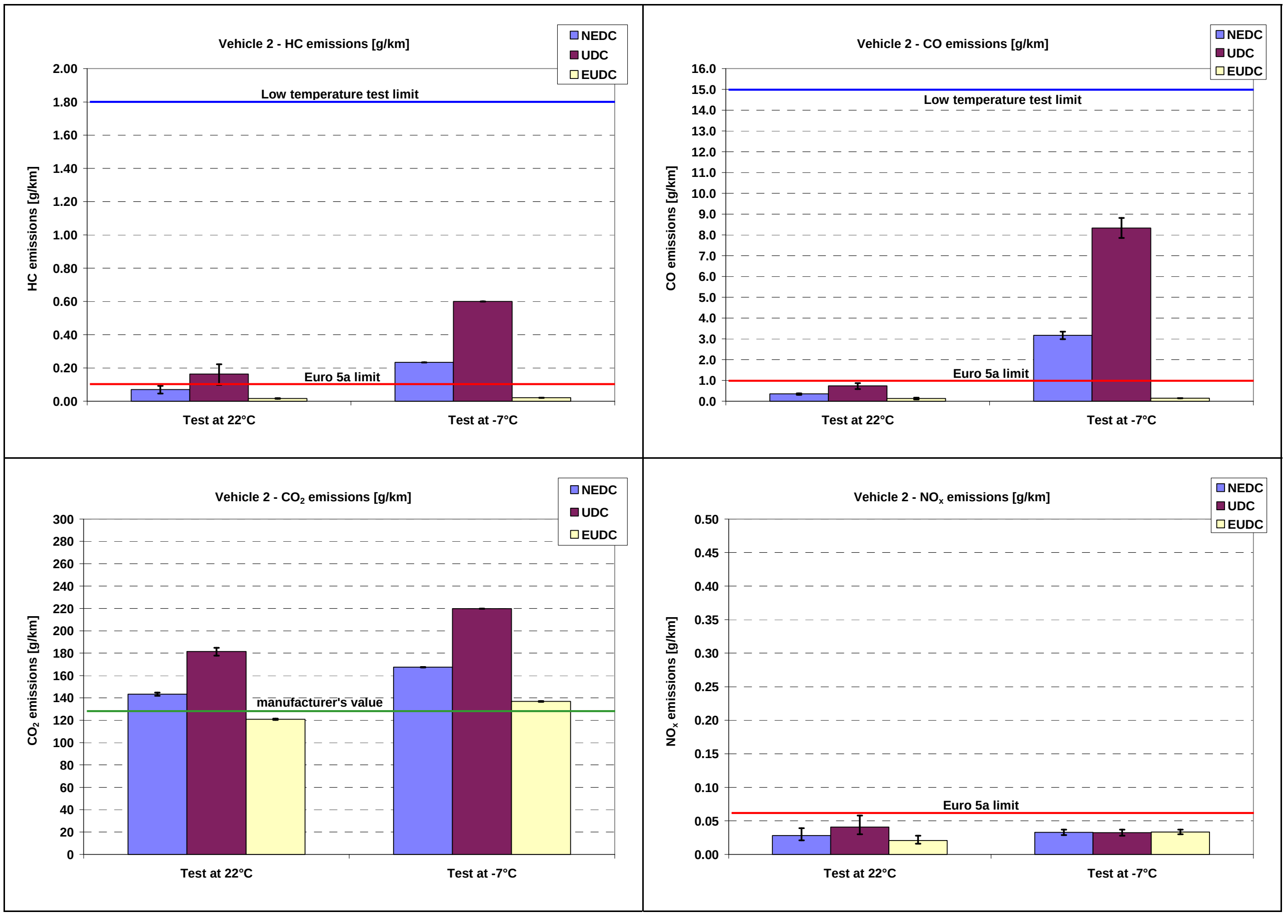


Figure 11 – Vehicle 2: Total HC, CO, CO_2 and NO_x emission measurements at 22°C and -7°C over the NEDC, UDC and EUDC driving cycles.

Figure 12 shows the second-by-second HC, CO and NO_x values measured over the NEDC at 22 and -7°C. The main characteristic was the increased concentrations of CO and HC at -7°C during the first 150 s of the cycle. This is mainly explained by the fact that the catalyst reached the full efficiency much later in the low temperature test.

NO_x emissions behave almost identically as the previous reported vehicle (Vehicle 1). The majority of NO_x mass was emitted during the cold start and the extra-urban part of the cycle. Apart from the emissions during the cold start, some of the NO_x peaks that can be noticed in the urban cycle during the deceleration phases were due to the fuel cut-off which is evidenced by corresponding lambda peaks. These shows that the air-fuel ratio became almost instantaneously lean when the vehicle's operation changed from steady speed and load to no load and deceleration. During the extra-urban part of the cycle NO_x were mainly emitted when the vehicle accelerated.

The lambda value pattern was typical of a port fuel injection gasoline engine with 3-way catalytic converter. The engine ran in stoichiometric condition (lambda=1) for most of the time. The difference with the direct injection Vehicle's 1 lambda pattern was evident.

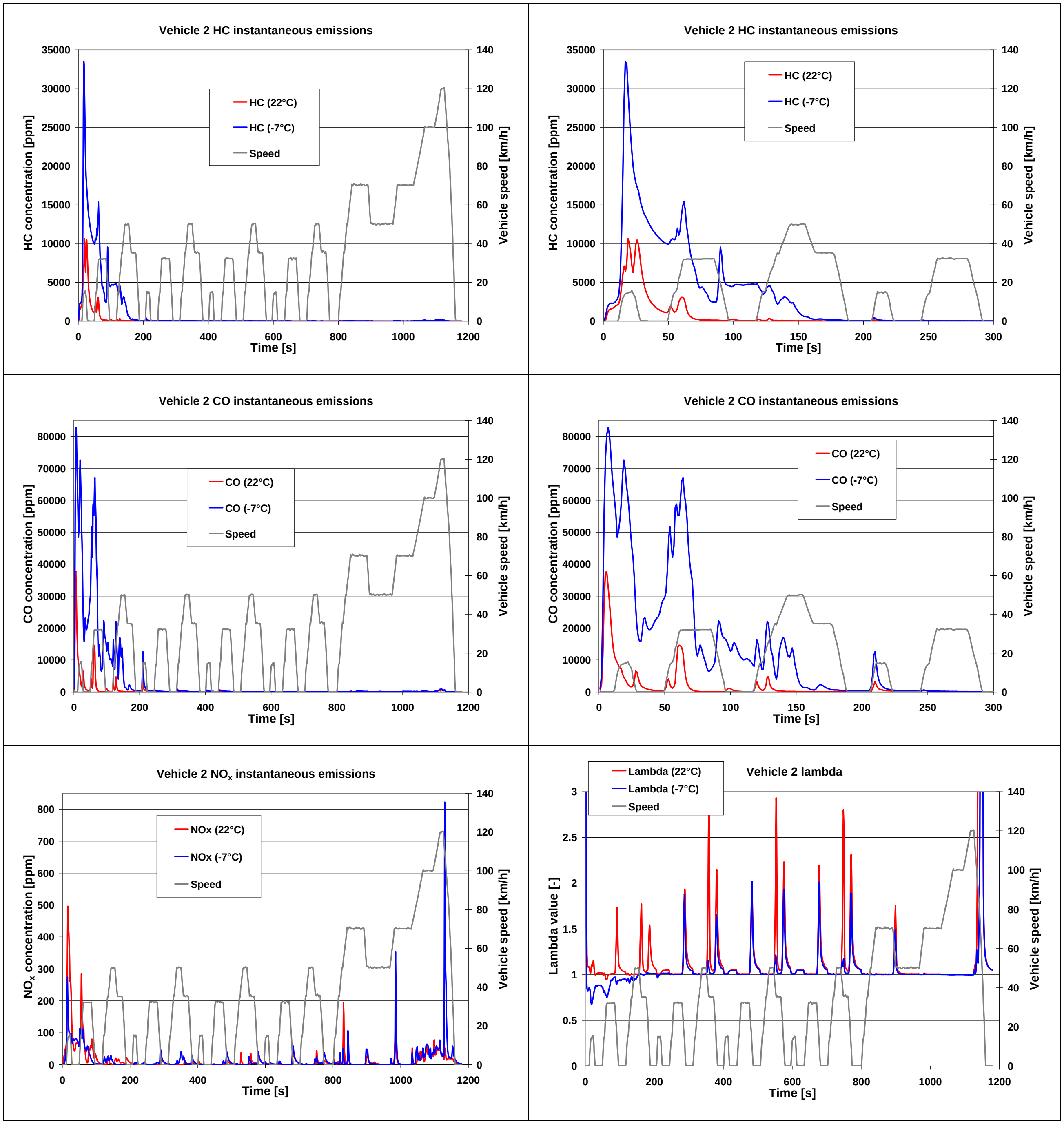


Figure 12 – Vehicle 2: Total HC, CO and NO$_x$ instantaneous emissions and lambda value over the NEDC driving cycle at 22°C and -7°C.

The cumulative gaseous emissions charts over the NEDC cycle at the two test temperatures are shown in the following Figure 13. The evolution for CO and total HC was almost identical. The emitted mass increased very quickly during the cold start while then it remained almost constant until half the extra-urban part of the cycle was covered. This could be explained by the very good efficiency of the catalyst that converted effectively these emissions at both the two test temperatures once it has reached the right working temperature. During the last part of the extra-urban part of the cycle, when the vehicle accelerated up to the maximum speed of the cycle (120 km/h), there was a slight increase of CO and HC may be due to the high exhaust flow rate.

As already pointed out for the previous vehicle, the NO_x cumulative emission pattern is quite different when compared to HC and CO. After the sharp increase during the cold start, the cumulative NO_x emissions increased very slowly during the urban part of the cycle. The slope of the NO_x mass started increasing again during the second half of the extra-urban part of the cycle and reached the maximum value with the last acceleration. This was more evident in the test at -7°C probably due to the increased chassis dynamometer loads.

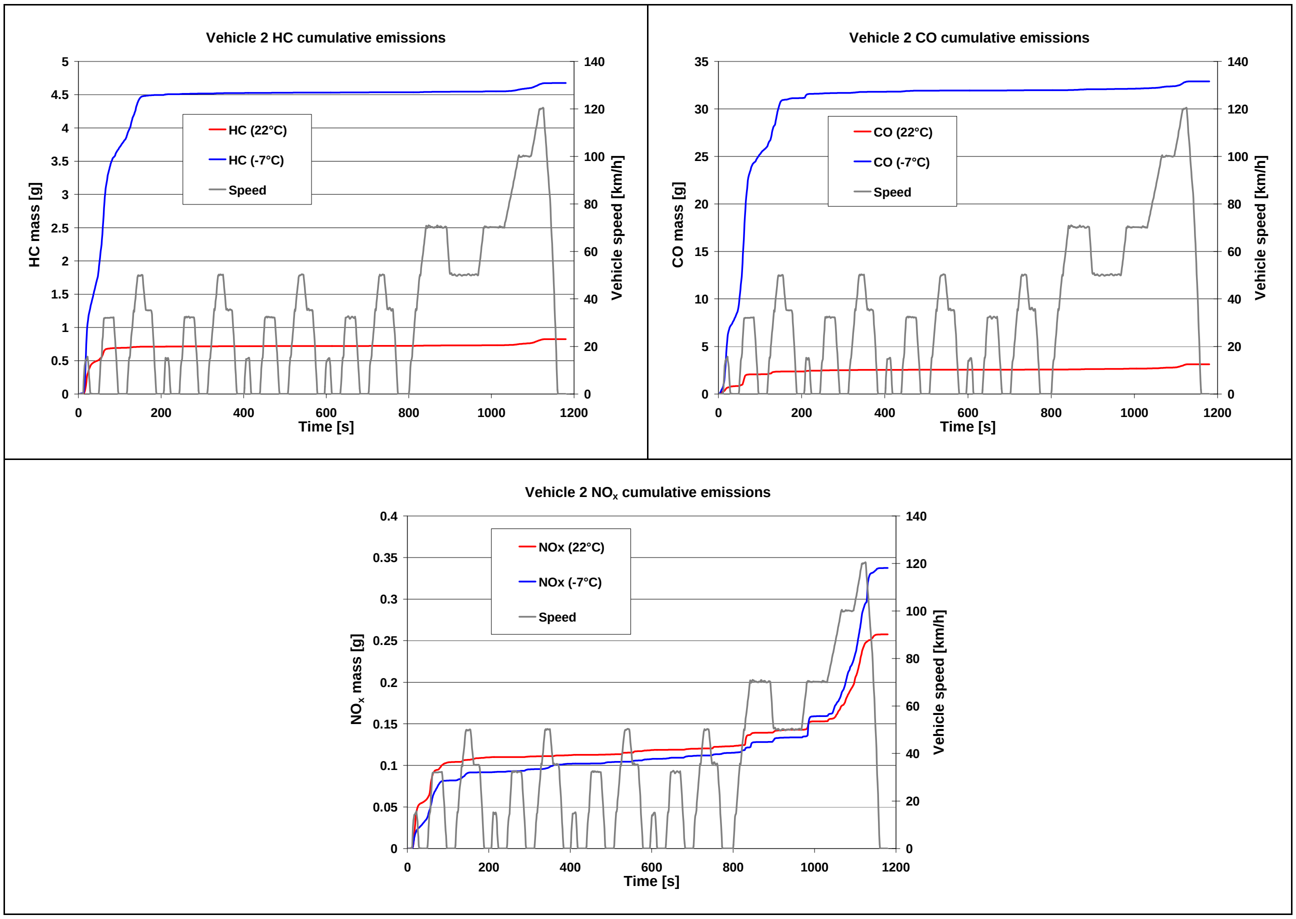


Figure 13 – Vehicle 2: Total HC, CO and NO_x cumulative mass emissions over the NEDC driving cycle at 22°C and -7°C.

VEHICLE 3

Table 13 provides the bag emissions and the fuel consumption measured over the NEDC (22°C) and UDC (22 & -7°C) cycles for Vehicle 3. Again, the vehicle complies with the relevant legislative limits both at 22°C over the NEDC cycle and at -7°C over the UDC cycle. Contrary to the two vehicles discussed above (Vehicle 1 and 2) in this case NO_x exhaust emissions in the low temperature test turned out to be one order of magnitude higher than the value measured at 22°C.

In Table 13 the values in the parentheses (where exist) refer to the type approval values for each pollutant and type of test. As for Vehicle 1, the CO_2 and fuel consumption measured values were higher than the type approval values. CO and total HC measured values were instead lower than the type approval values, especially in the Type VI test where the measured emission values were almost half as the type approval ones.

Table 13 – Measured gaseous emissions and fuel consumption for the Vehicle 1 over the NEDC (22°C) and UDC (22°C & -7°C) driving cycles (in parentheses the type approval data from KBA).

VEHICLE 3				
Emissions	**Unit**	**NEDC 22°C**	**UDC 22°C**	**UDC -7°C**
HC	g/km	0.038 (0.045)	0.096	0.623 (1.04)
CO	g/km	0.327 (0.454)	0.807	2.298 (4.61)
NO_x	g/km	0.022 (0.032)	0.016	0.464
CO_2	g/km	180.2 (166)	235.1 (225)	258.0
Fuel Consumption	l/100km	7.6 (7.1)	9.9 (9.7)	11.0

Figure 14 shows the bag emission values of Vehicle 3 measured over the NEDC, UDC and EUDC driving cycles at 22°C and -7°C in bar chart format. In the low temperature test, HC, CO, and NO_x emissions over the NEDC cycle increased 6.1, 2.7, 8.4 times respectively. The CO_2 emission increased by 8.4% over the NEDC.

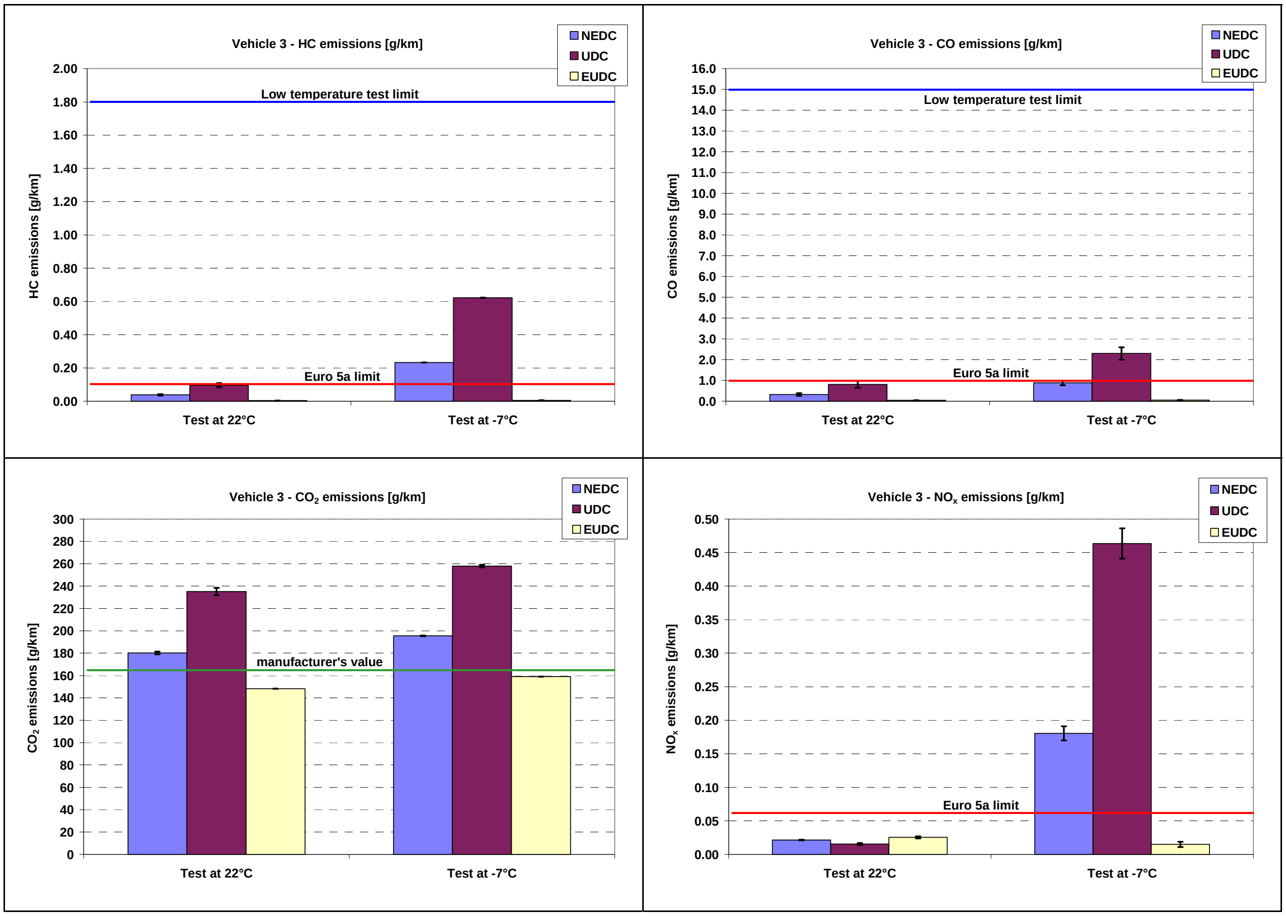


Figure 14 – Vehicle 3: Total HC, CO, CO_2 and NO_x bag emission values at 22°C and -7°C over the NEDC, UDC and EUDC driving cycles.

Figure 15 shows the instantaneous emission concentrations over the NEDC driving cycle at 22 and -7°C. As usual, in the -7°C test CO and HC concentrations increased remarkably during the cold start, when the warming up of the catalyst's substrate took place. At 22°C a sharp decrease of the emissions could be identified after about 50 s, while at -7°C the same sharp decrease took place after time 100 s implying that the catalyst reached the full efficiency much later.

The NO_x emissions profile was very different compared to the previous vehicles. At 22°C the majority of the NO_x was emitted during the extra-urban part of the cycle (EUDC), where the vehicle speed and load increased. The calculated lambda curve at 22°C was typical of a gasoline port fuel injection vehicle as its value was close to one during almost all the cycle. Lambda peaks can be seen during the deceleration phases when the fuel injection stopped (cut-off). However, during the very first seconds after the engine started and almost until the end of the warming up of the catalyst, the engine seemed to operate leaner as suggested by the lambda value above one. This behaviour was more pronounced in the low ambient temperature test. If the lambda values recorded over the NEDC cycle at -7°C and at 22°C are compared, it can be seen that the traces are quite different. In particular at -7°C, after about 100 s, the lambda value was well above 1 for a certain period of time suggesting that the engine ran lean. This could explain the NO_x spike registered at the same time. As a consequence, at -7°C the majority of NO_x emissions was emitted during the urban part of the cycle explaining the big difference with the value measured over the urban cycle at 22°C (see Figure 14). It is not clear whether this was due to a particular engine strategy adopted to reduce HC and CO emissions at low temperature or if this was due to other reason like, for instance, the higher resistance to progress used at -7°C.

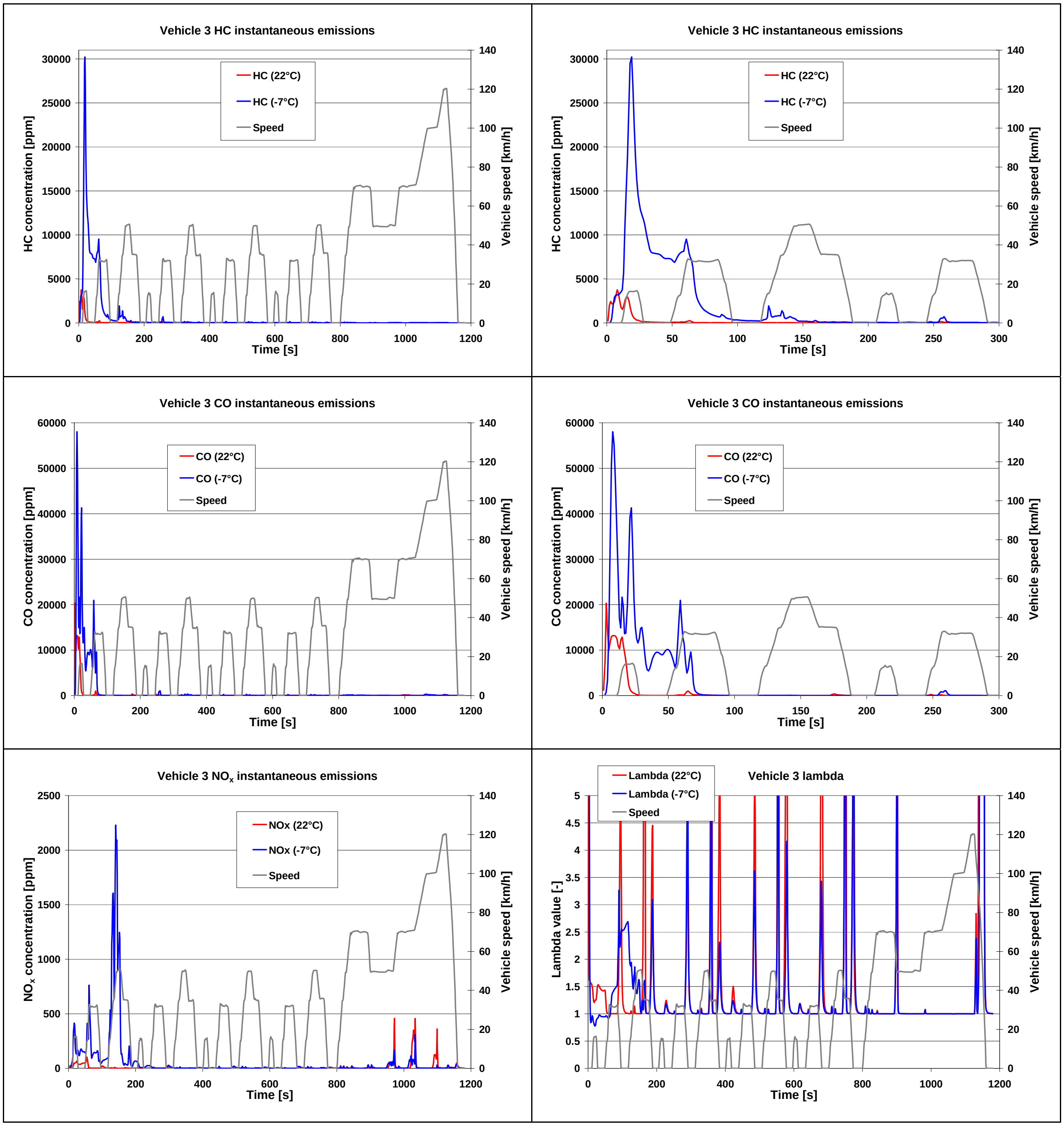


Figure 15 – Vehicle 3: Total HC, CO and NO_x instantaneous emissions and lambda value over the NEDC driving cycle at 22°C and -7°C.

The cumulative mass emissions of CO, HC and NO_x over the NEDC cycle at 22 and -7°C tests are presented in the following Figure 16. CO and total HC show the typical trend with a sharp increase during the cold start and then an almost flat curve until the end of the cycle. At -7°C the emission evolution was very similar, but with higher emissions of each pollutant over the first seconds of the cycle. As far as NO_x emissions are concerned, the plot shows again the dramatically different evolution when comparing the test performed at 22°C with the low temperature test.

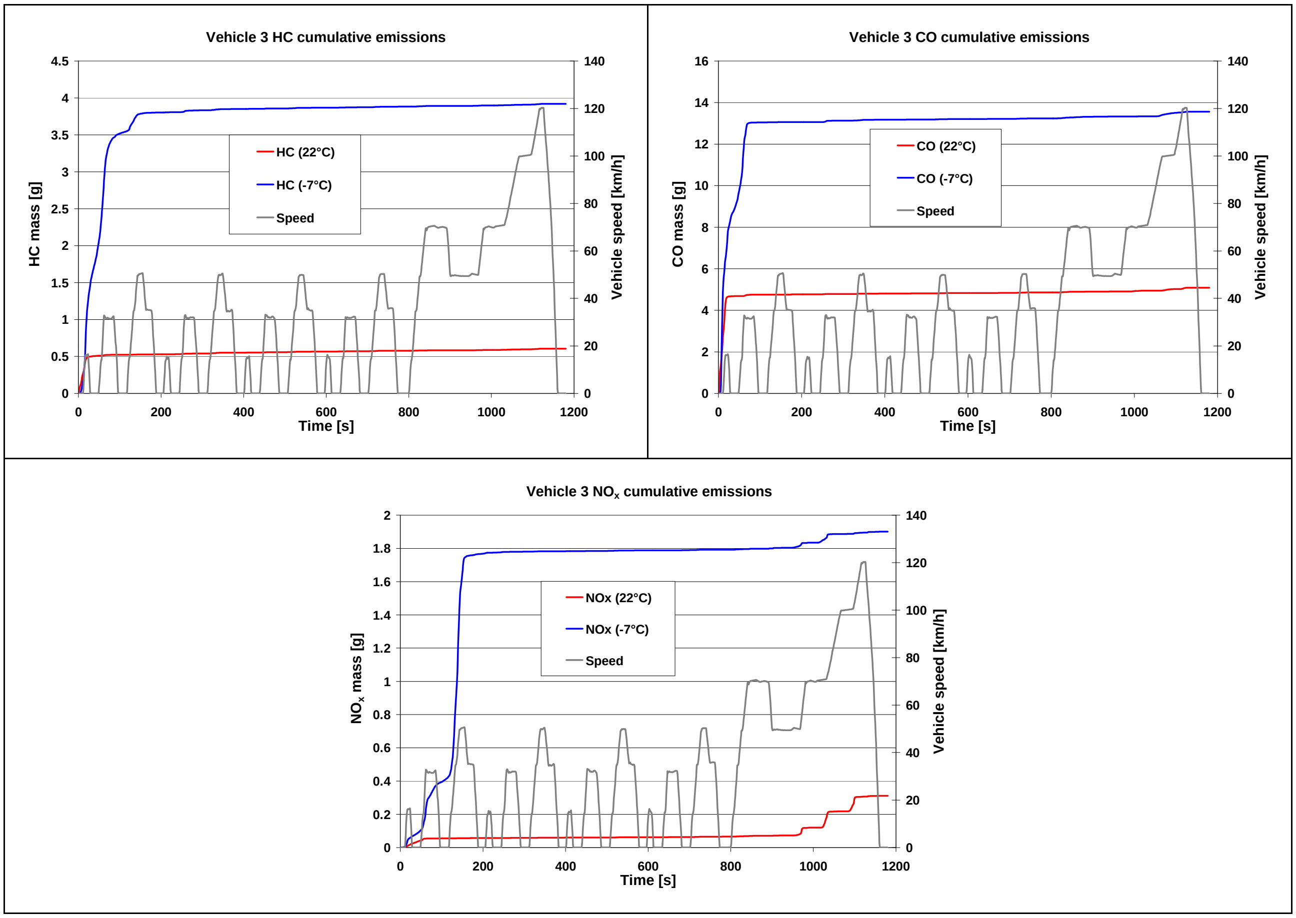


Figure 16 – Vehicle 3: Total HC, CO and NO_x cumulative mass emissions over the NEDC driving cycle at 22°C and -7°C.

VEHICLE 4

Table 14 provides the bag emission values of Vehicle 4. The results are referred to the NEDC (22°C) and UDC (22°C & -7°C) driving cycles. The tests have confirmed that the vehicle complies with the relevant legislative limits. The values given in the parentheses refer to the type approval data. The differences with the JRC measurements are low, especially for HC and NO_x emissions measured over the NEDC at 22°C. Again the measured CO_2 and fuel consumption values were higher than the type approval value. For this vehicle one value for gaseous emissions was available at -7°C due to a problem to the analyzers.

Table 14 – Measured gaseous emissions and fuel consumption for Vehicle 4 over the NEDC (22°C) and UDC (22°C & -7°C) driving cycles (in parentheses the type approval data from KBA).

VEHICLE 4				
Emissions	**Unit**	**NEDC 22°C**	**UDC 22°C**	**UDC -7°C**
HC	g/km	0.036 (0.040)	0.094	0.356 (0.424)
CO	g/km	0.344 (0.277)	0.522	1.671 (2.042)
NO_x	g/km	0.015 (0.014)	0.030	0.075
CO_2	g/km	138.2 (119)	165.6 (149)	191.4
Fuel Consumption	l/100km	5.8 (5.1)	7.0 (6.4)	8.2

Figure 17 shows the bag emission values of this vehicle in bar chart format over the NEDC, UDC and EUDC driving cycles at the two different test temperatures. Concerning total HC and CO emissions, the increase in the -7°C test over the NEDC was 3.7 and 2.1 times respectively. In the -7°C test the CO_2 emission value increased by 10.4%, almost fully in line with the increased dyno loads (+10%) prescribed for the low temperature test. Finally, at -7°C NO_x emissions over the NEDC cycle increased 2.2 times compared to the ambient temperature test.

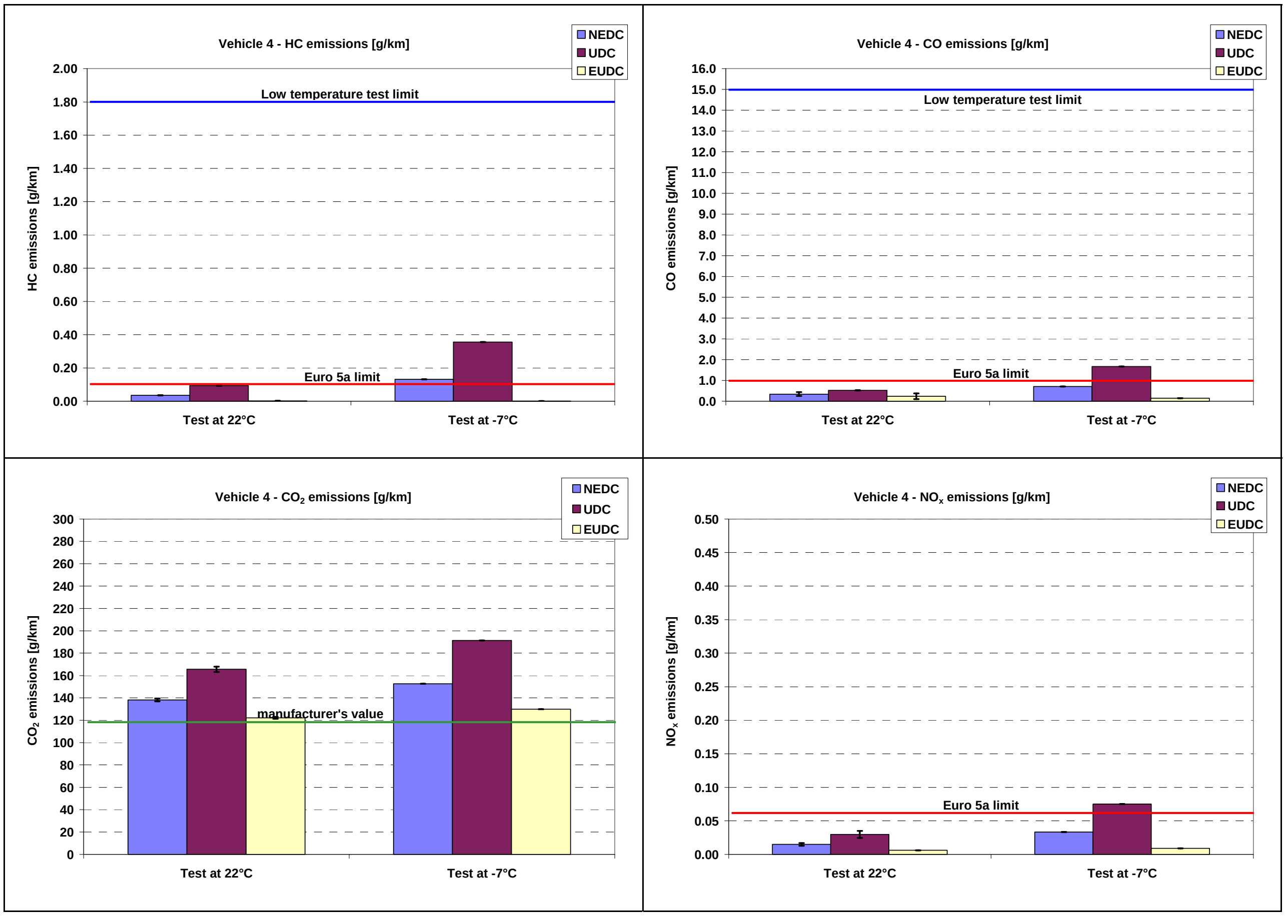


Figure 17 – Vehicle 4: Total HC, CO, CO_2 and NO_x measured bag emission values at 22°C and -7°C over the NEDC, UDC and EUDC driving cycles.

Figure 18 shows the instantaneous emissions for HC, CO and NO_x and the lambda value recorded over the NEDC driving cycle at the two test temperatures. Looking at the HC and CO emissions pattern, the catalyst reached its full efficiency within the first 80 s, regardless the ambient temperature. At -7°C the CO and HC concentrations increased significantly due to the enrichment of the air-fuel mixture.

Concerning NO_x emissions, although an important fraction was emitted during the cold start, there were also peaks of NO_x over the whole duration of the cycle. These peaks correspond to the acceleration phases, where the engine load increased suddenly, and to the deceleration phases (fuel cut-off).

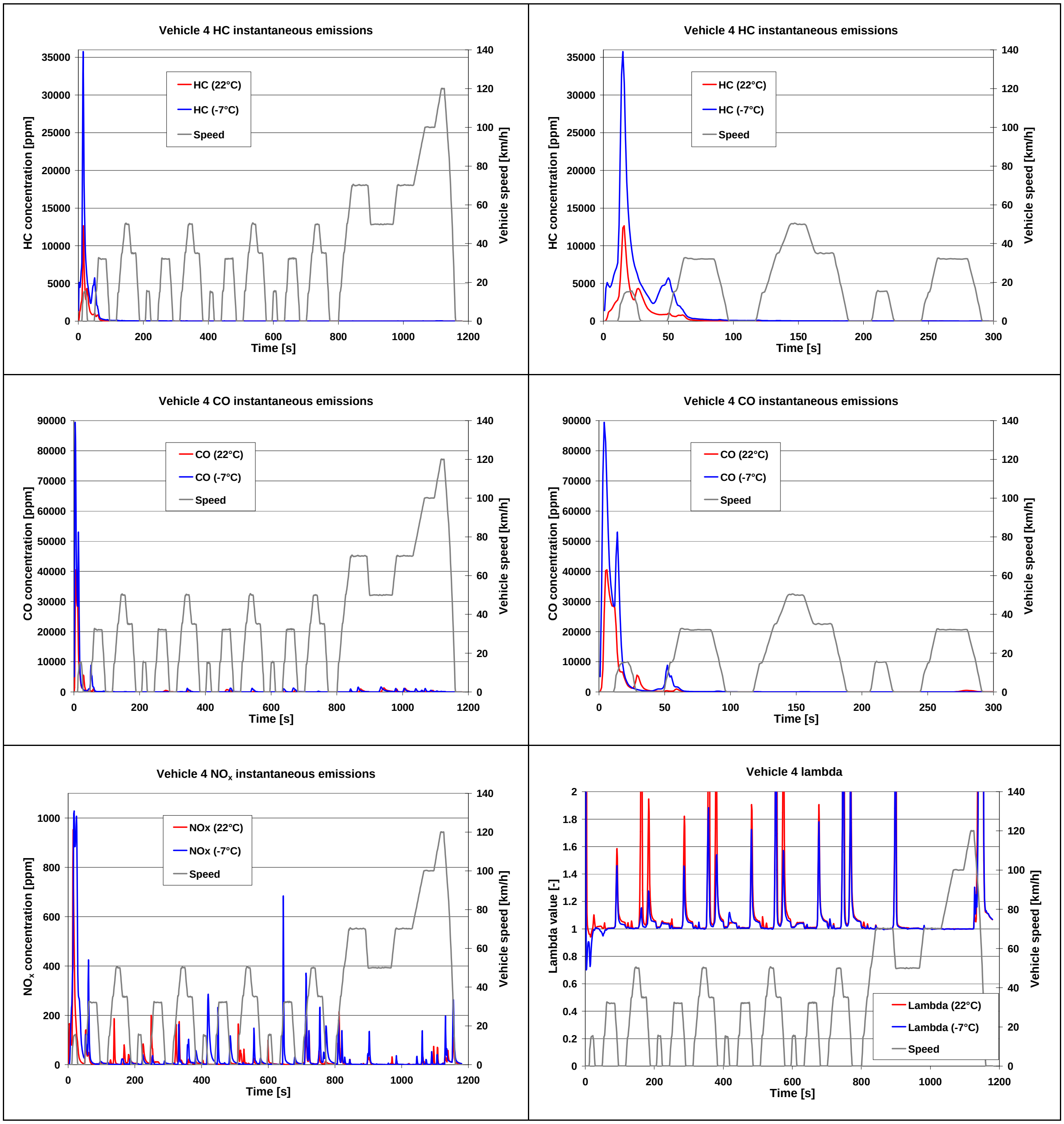


Figure 18 – Vehicle 4: Total HC, CO and NO_x instantaneous emissions and lambda value over the NEDC driving cycle at 22°C and -7°C.

Figure 19 shows the cumulative emissions of HC, CO and NO_x over the NEDC cycle in both the low and ambient temperature tests. The profile for HC and CO emission was almost identical, with the majority of them emitted during the warming up of the catalyst substrate. As far as CO is concerned, there was a liner increase also over the extra-urban part of the cycle, where the engine load increased. It is speculated that this behaviour could be attributed to the relatively small catalyst: As it has already mentioned in the previous Figure 18, the warming phase of the catalyst was very short, which is also an indicator of small volume of the catalyst. When the engine ran at higher loads and emited increased quantities of CO, the size of the catalyst might not was sufficient to oxidize effectively the engine-out CO emissions.

The NO_x cumulative emissions are shown in Figure 19. At -7°C, NO_x emissions during the warming up were almost doubled compared with the respective at 22°C. After the warming up period (first 80 s of the cycle), the NO_x cumulative mass emission increased almost linearly, due to the previously mentioned NO_x peaks occurring during the whole duration of the driving cycle and which seem to be hardly dependent on the ambient temperature.

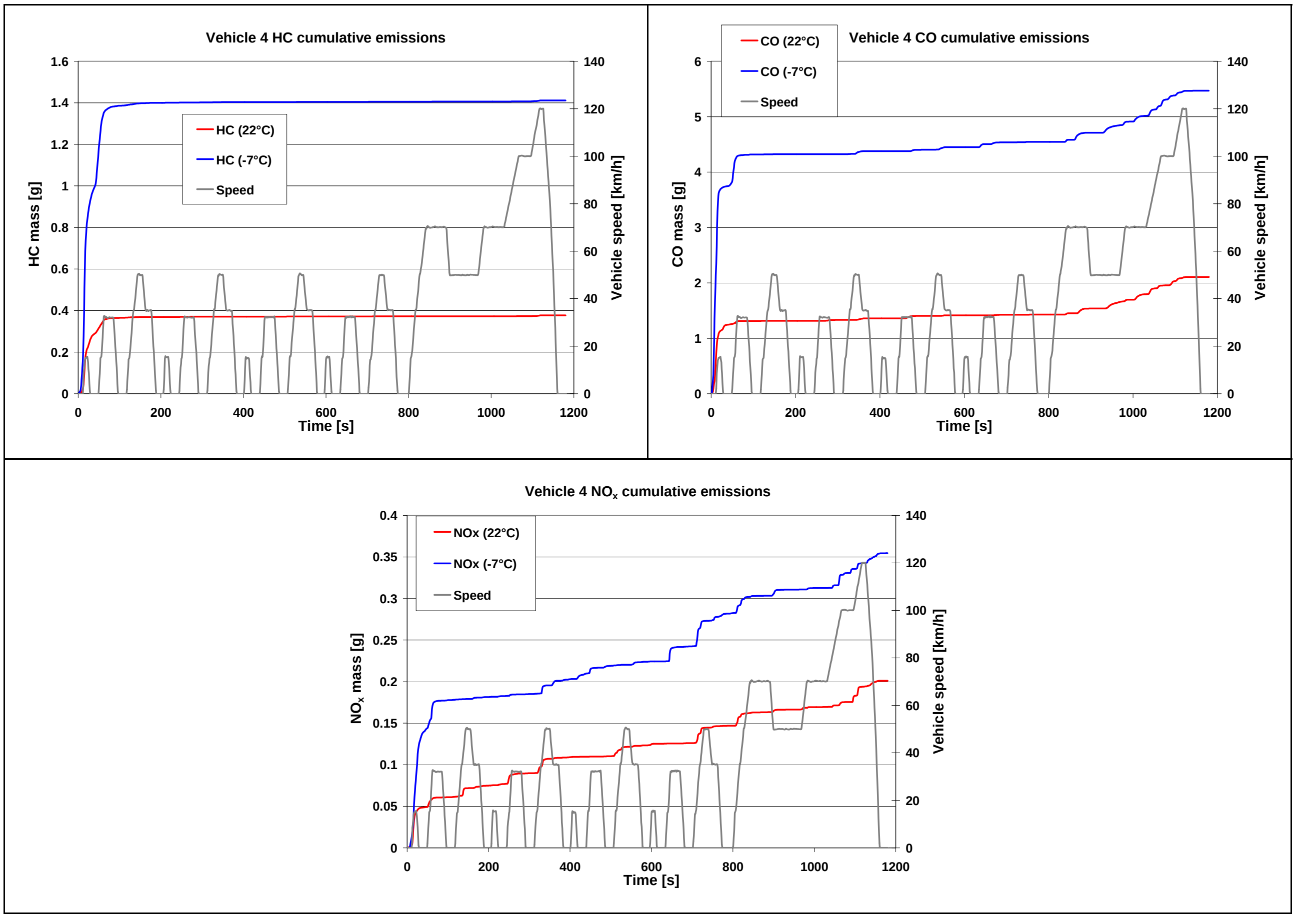


Figure 19 – Vehicle 4: Total HC, CO and NO_x cumulative mass emissions over the NEDC driving cycle at 22°C and -7°C.

VEHICLE 5

Table 15 provides the emission values and the fuel consumption measured over the NEDC (22°C) and the UDC (22°C & -7°C) cycles for Vehicle 5. The vehicle complies with the legislative limits in both the ambient (NEDC 22°C) and low temperature (UDC -7°C) tests. The respective type approval values where available only for Type I test at 22°C, given in parentheses.

Table 15 – Measured gaseous emissions and fuel consumption for Vehicle 5 over the NEDC (22°C) and UDC (22°C & -7°C) driving cycles (in parentheses data from the vehicle manual).

VEHICLE 5				
Emissions	**Unit**	**NEDC 22°C**	**UDC 22°C**	**UDC -7°C**
HC	g/km	0.036 (0.033)	0.093	0.607
CO	g/km	0.239 (0.286)	0.607	3.135
NO_x	g/km	0.007 (0.010)	0.017	0.007
CO_2	g/km	155.9 (139)	192.2 (179)	228.3
Fuel Consumption	l/100km	6.7 (6.1)	8.3 (7.8)	10.1

Figure 20 shows the bag emission values measured over the NEDC, UDC and EUDC at the two different test temperatures in bar chart format. HC and CO emissions at -7°C over the NEDC cycle increased by 6.2 and 5 times respectively. The emission values over the UDC cycle were 0.6 g/km and 3.13 g/km, which were below the current legislative limits.

Vehicle 5 emitted 0.007 g/km of NO_x emissions over the NEDC cycle at 22°C, and the respective value in the -7°C test decreased by 41% to 0.004 g/km. CO_2 emissions increased by 15% over the NEDC when the test conducted at -7°C.

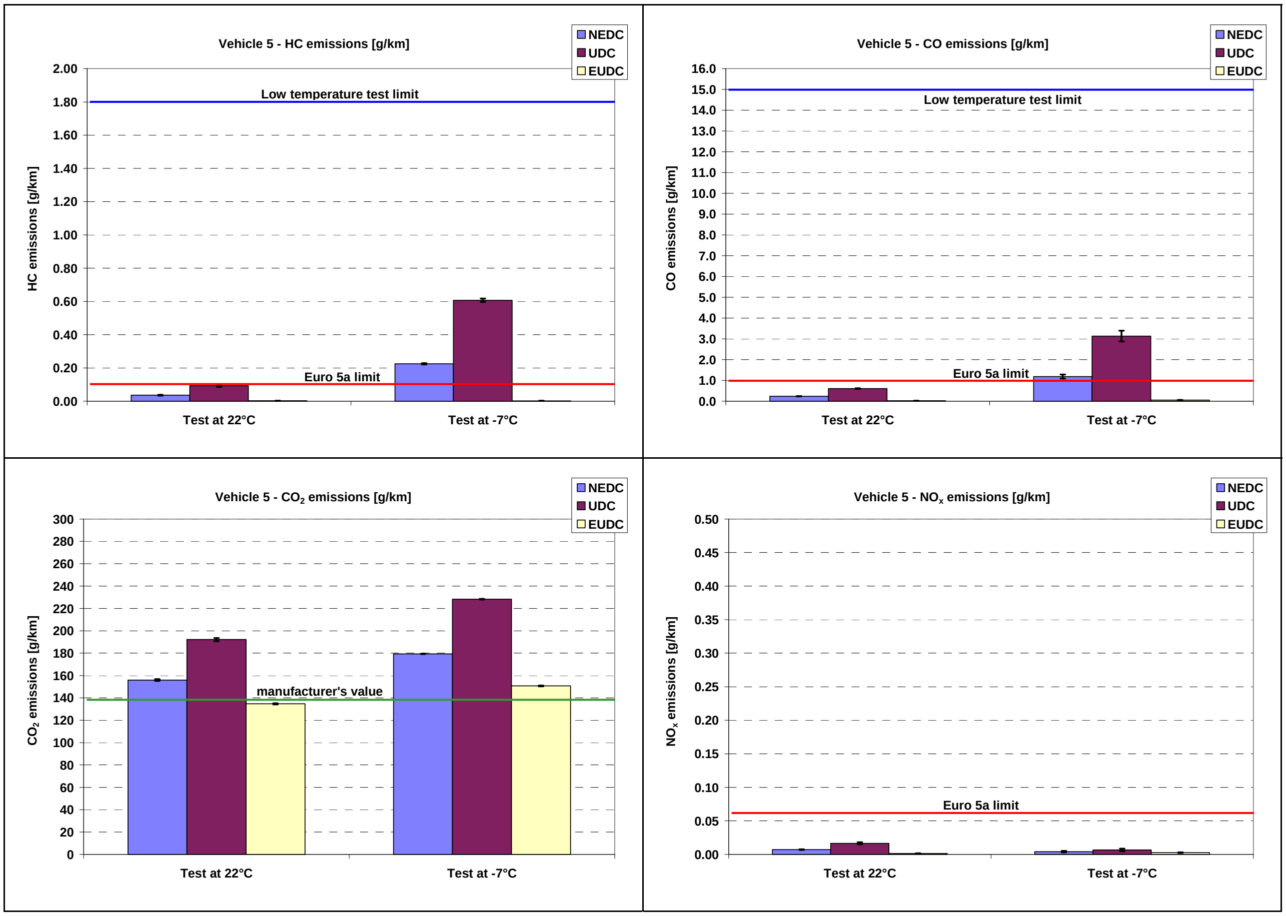


Figure 20 – Vehicle 5: Total HC, CO, CO_2 and NO_x emission measurements at 22°C and -7°C over the NEDC, UDC and EUDC driving cycles.

Figure 21 shows the second-by-second HC and CO concentration values measured over the NEDC at 22°C and -7°C. Second-by-second NO_x data are not available for the specific vehicle due to a problem to the respective analyzer. The emission pattern during the first seconds is typical of petrol car equipped with a PFI engine and in line with those already seen for the other vehicles.

At -7°C the concentration of CO and HC during the first 100 s of the cycle increased compared to the values recorded at 22°C. At -7°C the catalyst reached its full efficiency about after the first 100 s of the cycle while at 22°C test after 50 s. Once the catalyst has reached its full efficiency the CO and HC emission values were almost zero over the rest of the cycle, even when the engine ran at increased load during the extra-urban part of the cycle.

The lambda value pattern was typical of a petrol engine with a 3-way catalytic converter and a port fuel injection engine. The engine ran mainly in stoichiometric operation (lambda=1) and there was no significant difference between the traces calculated at the two different test temperatures, apart from the initial period of the extended air-fuel mixture enrichment at -7°C.

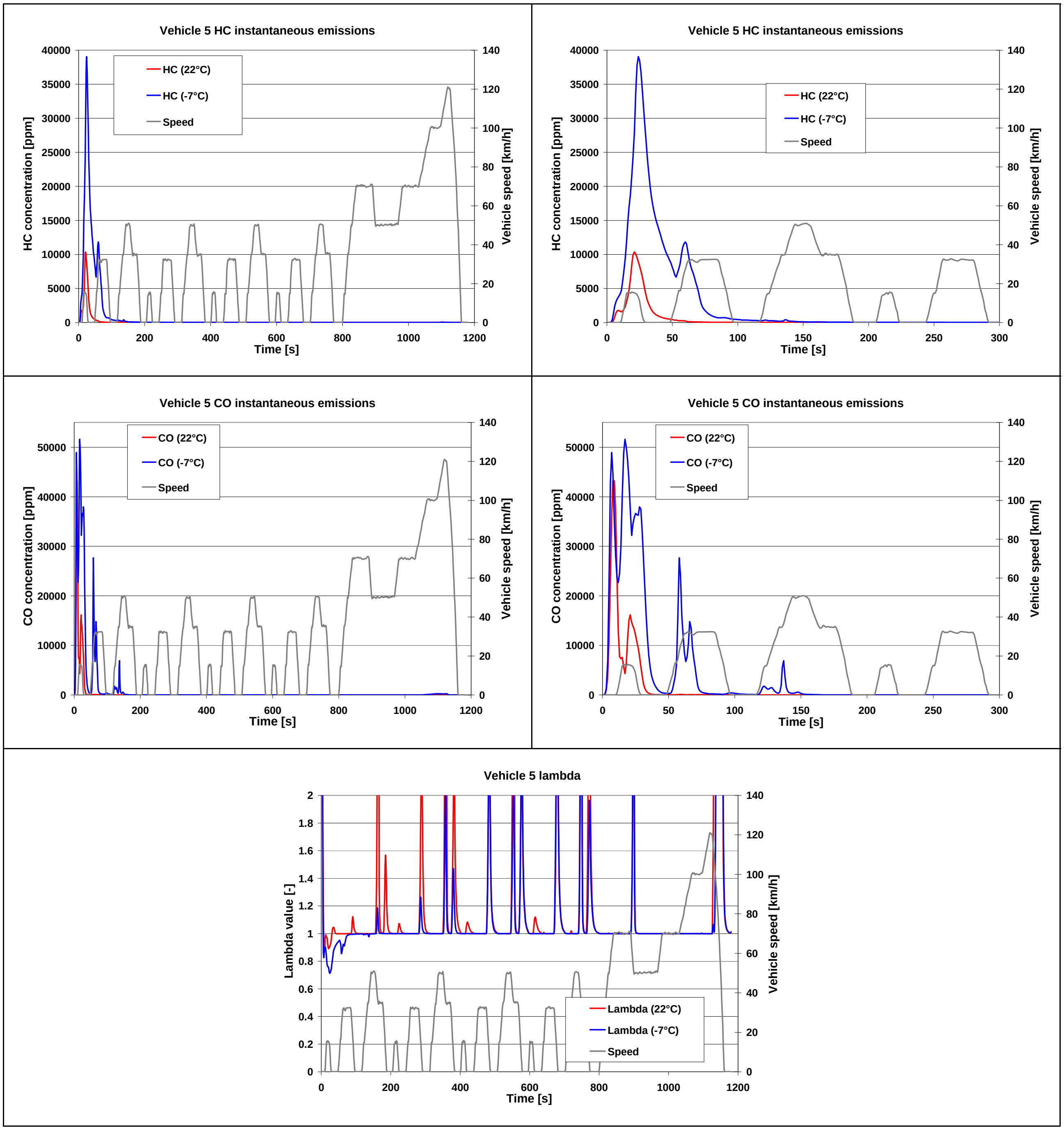


Figure 21 – Vehicle 5: Total HC and CO instantaneous emissions and lambda value over the NEDC driving cycle at 22°C and -7°C.

The cumulative mass emissions for CO and total HC over the NEDC cycle at the two ambient temperatures are shown in the following Figure 22. The evolution of total HC and CO is almost identical. During the cold start the emitted mass increased rapidly then, for total HC, the value remained pretty constant until the end of the cycle. For CO there was a slight increase during the last phase of the extra-urban part of the cycle, when the vehicle accelerated and the engine load increased.

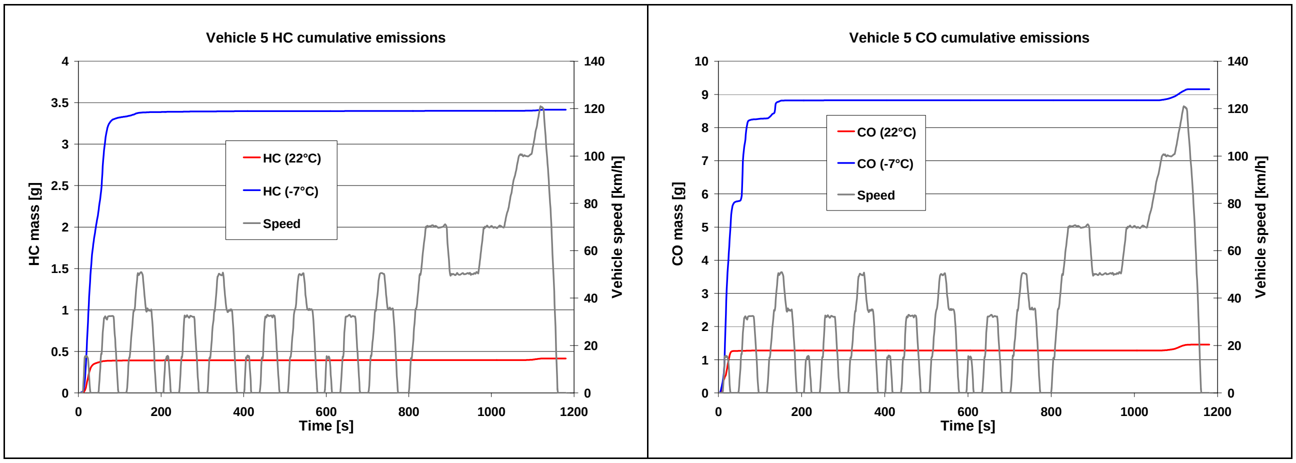


Figure 22 – Vehicle 5: Total HC and CO cumulative mass emissions over the NEDC driving cycle at 22°C and -7°C.

Vehicle 5 was tested for particulate matter and particle number emissions as well, at both test temperatures. Figure 23 shows the PM and PN emission results for both the ambient and low temperature tests. PM was measured over the NEDC and is expressed in mg/km, while PN is available also for the UDC and EUDC cycles and is expressed in particle (#)/km. The PM emission values doubled when the test was conducted at -7°C. Although this increase of PM at -7°C, the emission level still remained at 2 mg/km, quite below the current Euro 5b legislative limit of 4.5 mg/km, which is applicable only on G-DI gasoline vehicles.

The PN emission value in the 22°C test was 2.14×10^{11} #/km (NEDC cycle), below the Euro 5b/Euro 6 limit of 6.0×10^{11} #/km applicable to diesel vehicles. In the -7°C test this PN value increased by one order of magnitude, reaching 1.55×10^{12} #/km which is above the previously mentioned limit. The result referred to the UDC cycle (-7°C) was 4.14×10^{12} #/km.

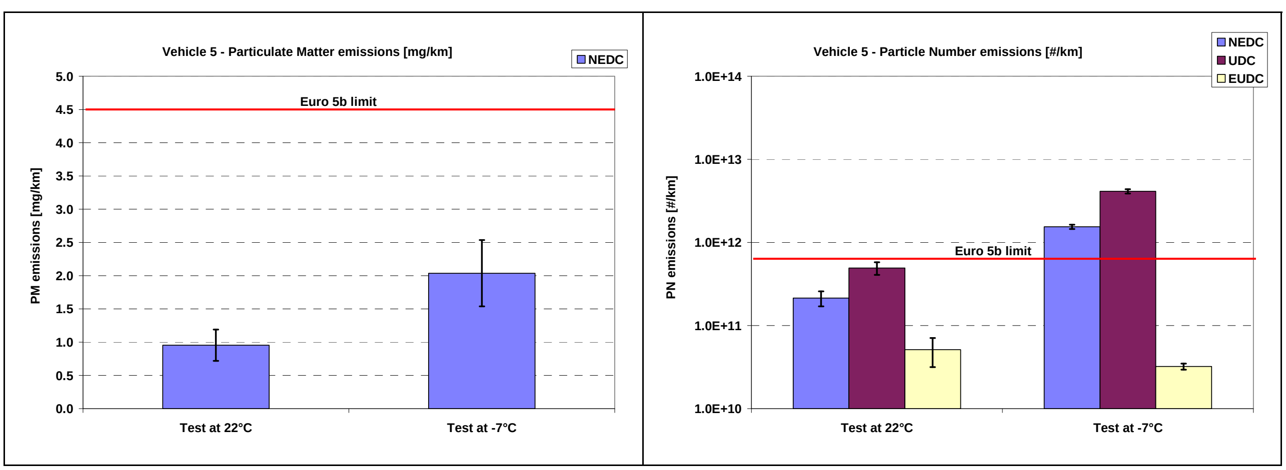


Figure 23 – Vehicle 5: PM emission measurement over the NEDC and PN emission values over the NEDC, UDC and EUDC driving cycles at 22°C and -7°C.

Figure 24 shows the instantaneous PN rate (in terms of #/s) over the NEDC cycle at both the test temperatures. The particles were emitted mainly at the beginning of the cycle, due to cold start effect. At -7°C there were more PN peaks which were also higher than at 22°C. The cumulative PN emissions over the NEDC cycle for both the test temperatures are also shown in the same Figure. At both temperatures most of the particles were emitted during the first 150 s of the cycle. It is also obvious the almost one order of magnitude increase of PN emissions in -7°C test.

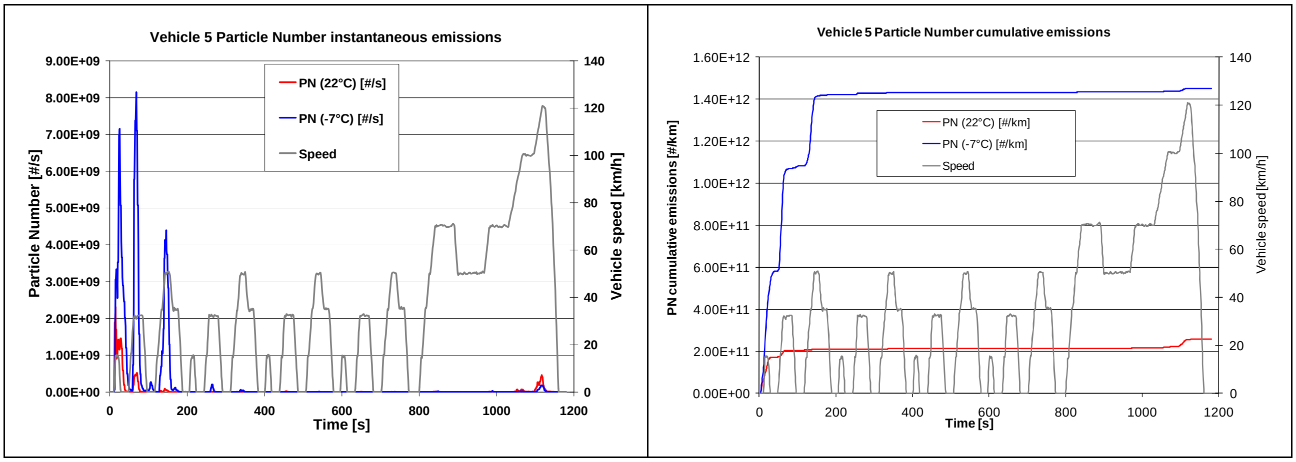


Figure 24 – Vehicle 5: Instantaneous PN rate and cumulative values over the NEDC driving cycle at 22°C and -7°C.

VEHICLE 6

Table 16 provides the bag emission values and the fuel consumption measured over the NEDC (22°C) and the UDC (22°C & -7°C) cycles for Vehicle 6. The vehicle complies with the legislative limits in both the test at ambient (NEDC 22°C) and low temperature (UDC -7°C). The respective type approval emission values were not also available for the specific vehicle. However, the CO_2 and fuel consumption type approval values (NEDC and UDC at 22°C) are given in parentheses. In this case the measured at JRC CO_2 and fuel consumption values were quite close to the respective type approval values. This vehicle was equipped with "start-stop" system, which was enabled during the measurements at JRC.

Table 16 – Measured gaseous emissions and fuel consumption for Vehicle 6 over the NEDC (22°C) and UDC (22°C & -7°C) driving cycles (in parentheses type approval values).

VEHICLE 6				
Emissions	**Unit**	**NEDC 22°C**	**UDC 22°C**	**UDC -7°C**
HC	g/km	0.033	0.089	0.573
CO	g/km	0.471	0.779	3.224
NO_x	g/km	0.008	0.019	0.070
CO_2	g/km	131.0 (124)	155.3 (160)	182.3
Fuel Consumption	l/100km	5.5 (5.4)	6.6 (6.9)	7.9

Figure 25 shows the bag emission values measured over the NEDC, UDC and EUDC driving cycles at the two different temperatures in bar chart format. The total HC and CO emissions measured at -7°C over the NEDC cycle increased by 6.4 and 2.9 times respectively. However, the Type VI test (UDC) total HC and CO resulted to be 0.573 g/km and 3.224 g/km respectively, values that were below the legislative limits.

Vehicle 6 emitted 0.008 g/km NO_x over the NEDC cycle at 22°C while the respective value in the -7°C test increased 3.5 times (0.026 g/km). Over the UDC at -7°C, Vehicle 6 emitted 0.070 g/km of NO_x. CO_2 emissions increased over the NEDC at -7°C by 13.9%.

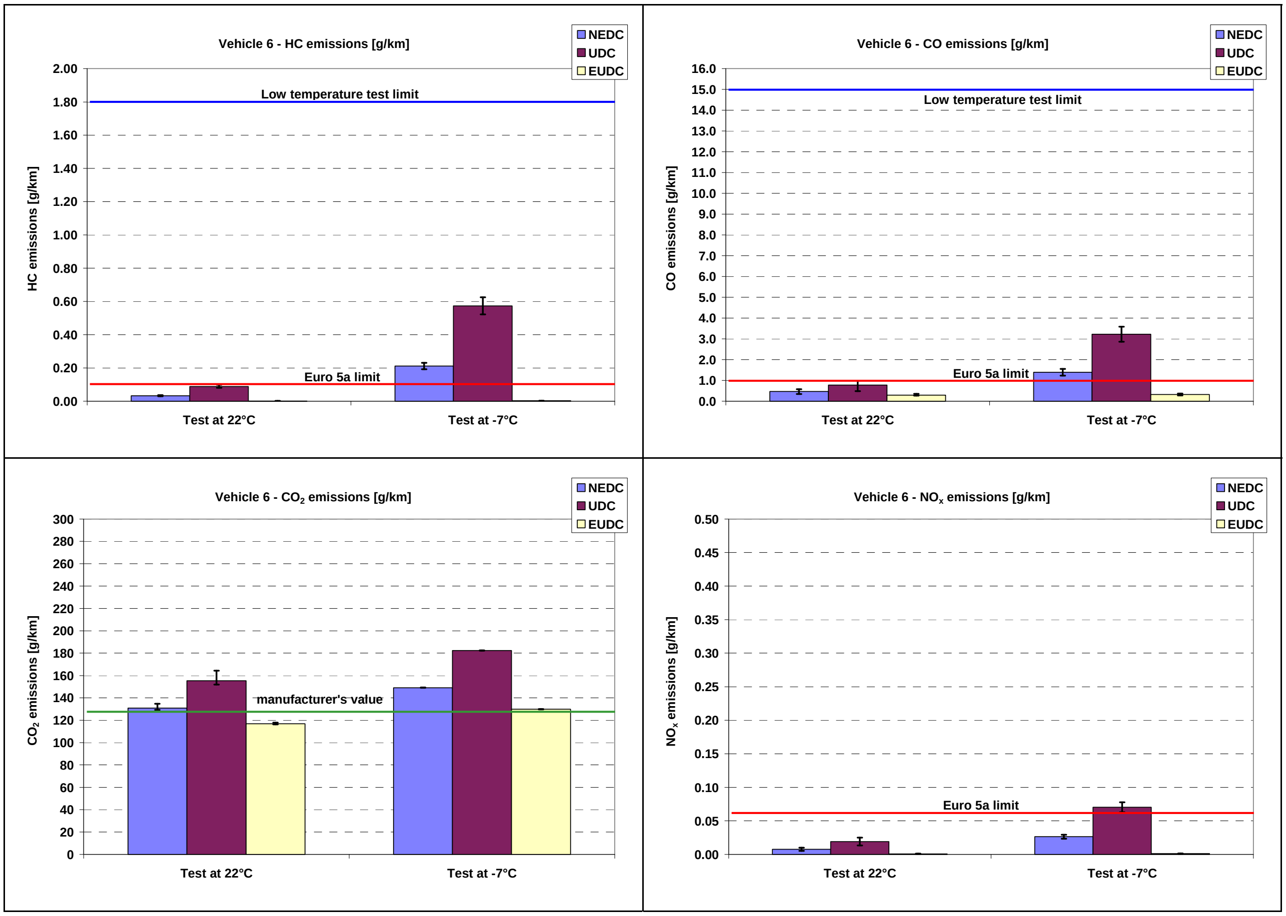


Figure 25 – Vehicle 6: Total HC, CO, CO_2 and NO_x emission measurements at 22°C and -7°C over the NEDC, UDC and EUDC driving cycles.

Figure 26 shows the instantaneous gaseous emission for HC, CO, NO_x and the lambda value over the NEDC driving cycle at the two test temperatures. After the typical peak occurring during the first seconds, CO and HC concentrations decreased to almost zero. This happened after about 70 s at 22°C and after about and 150 s at -7°C.

The majority of NO_x was also emitted during the cold start phase. Over the rest of the cycle NO_x emissions remained very low.

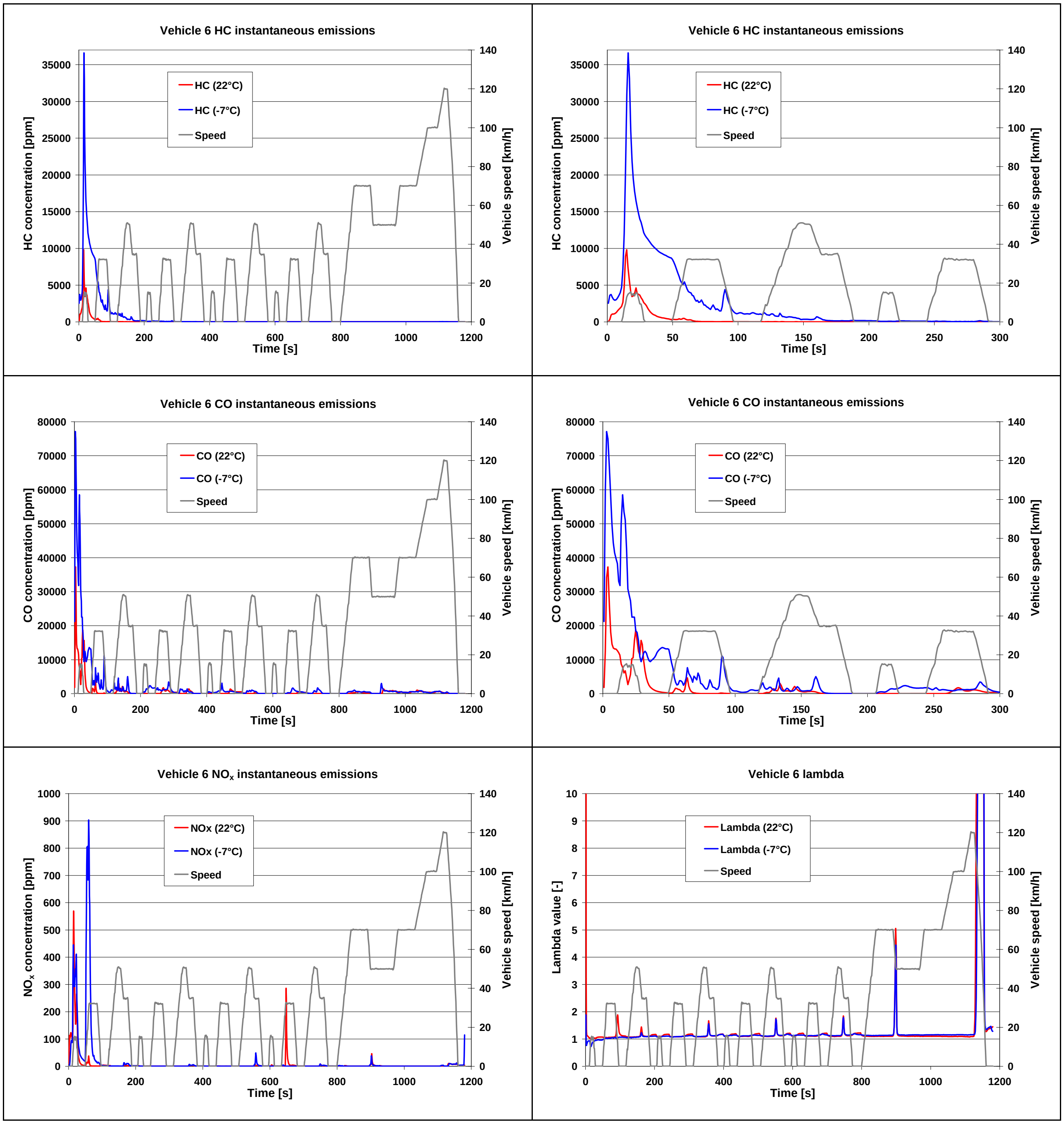


Figure 26 – Vehicle 6: Total HC, CO and NO_x instantaneous emissions and lambda value over the NEDC driving cycle at 22°C and -7°C.

Figure 27 shows the cumulative emissions of HC, CO and NO_x over the NEDC cycle in both low and ambient temperature test. Their behaviour is almost identical. For each pollutant the majority of the mass was emitted while the catalyst was warming up. Some additional quantity of CO was emitted over the extra-urban part of the cycle.

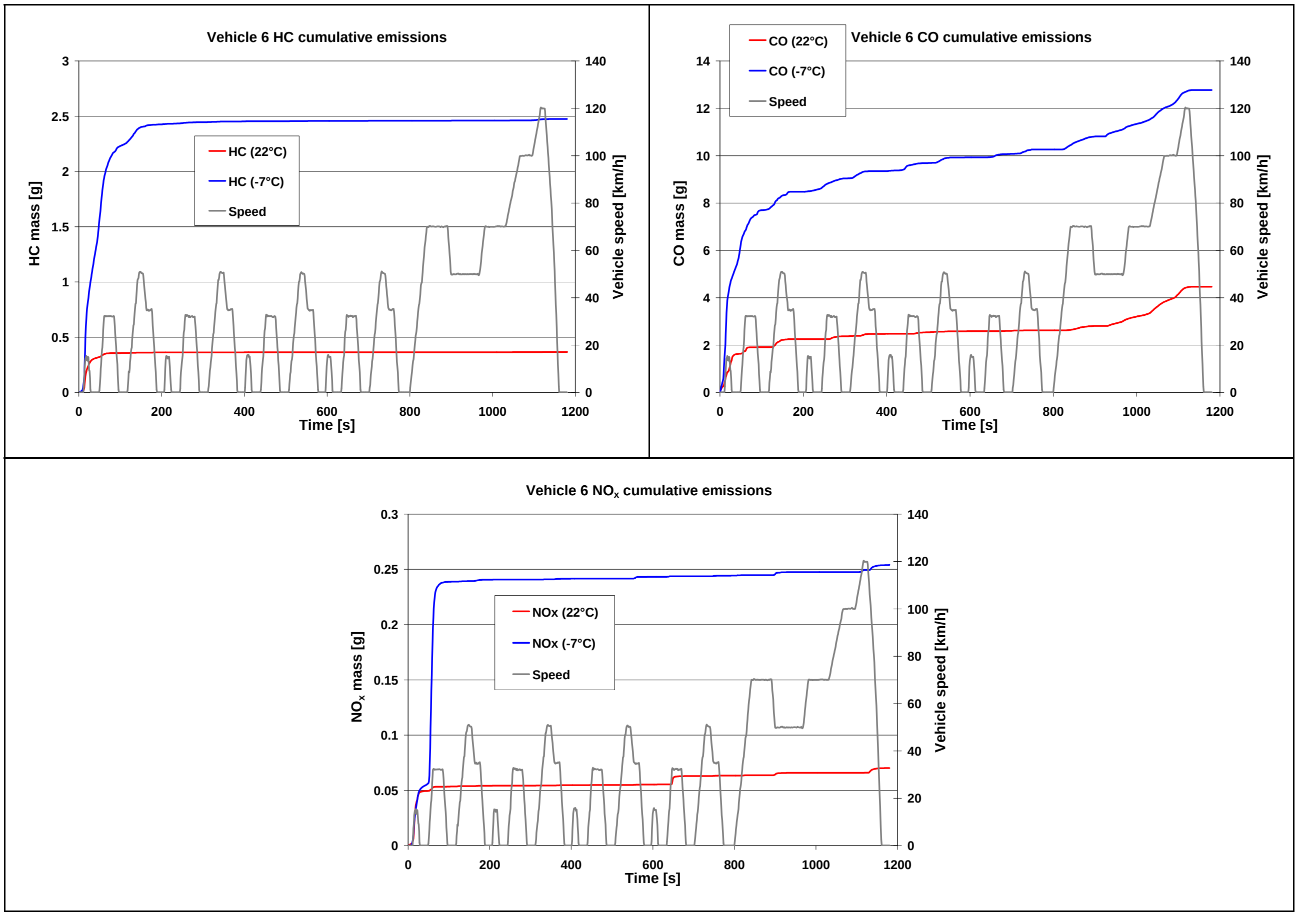


Figure 27 – Vehicle 6: Total HC, CO and NO_x cumulative mass emissions over the NEDC driving cycle at 22°C and -7°C.

VEHICLE 7

Table 17 provides the average bag emission values and fuel consumption for Vehicle 7 over NEDC (22°C) and over the urban part of the cycle UDC (22°C and -7°C).

Table 17 – Measured gaseous emissions and fuel consumption for Vehicle 7 over the NEDC (22°C) and UDC (22°C & -7°C) driving cycles (in parentheses the type approval data from KBA data base).

VEHICLE 7				
Emissions	**Unit**	**NEDC 22°C**	**UDC 22°C**	**UDC -7°C**
HC	g/km	0.078 (0.055)	0.201	0.598 (1.009)
CO	g/km	0.554 (0.631)	1.408	4.633 (4.061)
NO_x	g/km	0.036 (0.029)	0.091	0.126
CO_2	g/km	175.8 (167)	244.9 (221)	284.1
Fuel Consumption	l/100km	7.4 (7.1)	10.4 (9.4)	12.3

Figure 28 shows the bag gaseous emission values for total HC, CO, CO_2 and NO_x at 22°C and -7°C measured over the NEDC, UDC and EUDC driving cycles. In the plots the Euro 5a limits for CO, total HC and NO_x (1, 0.1 and 0.06 g/km respectively) for Type I test (Category M – Passenger Vehicles) over the NEDC cycle are indicated by a red solid line. The Type VI low temperature test limits for CO and total HC (15 and 1.8 g/km respectively) are indicated by a blue solid line. The manufacturer's CO_2 emission value (167 g/km) over the NEDC cycle is indicated in the respective chart by a green solid line.Vehicle 7 was equipped with a direct injection engine, running in stoichiometric mode. CO and total HC increased 3 times over the NEDC when the test conducted at -7°C, while the respective NO_x emissions increased 1.4 times. In Type VI test Vehicle 7 CO emissions measured at JRC were in line with type approval data (around 4 g/km), while total HC emissions were measured lower than the type approval value (0.598 instead of 1.009 g/km over UDC at -7°C). Over the UDC Vehicle 7 emitted 0.126 g/km of NO_x.

CO_2 emissions increased over the NEDC at -7°C by 15.7%.

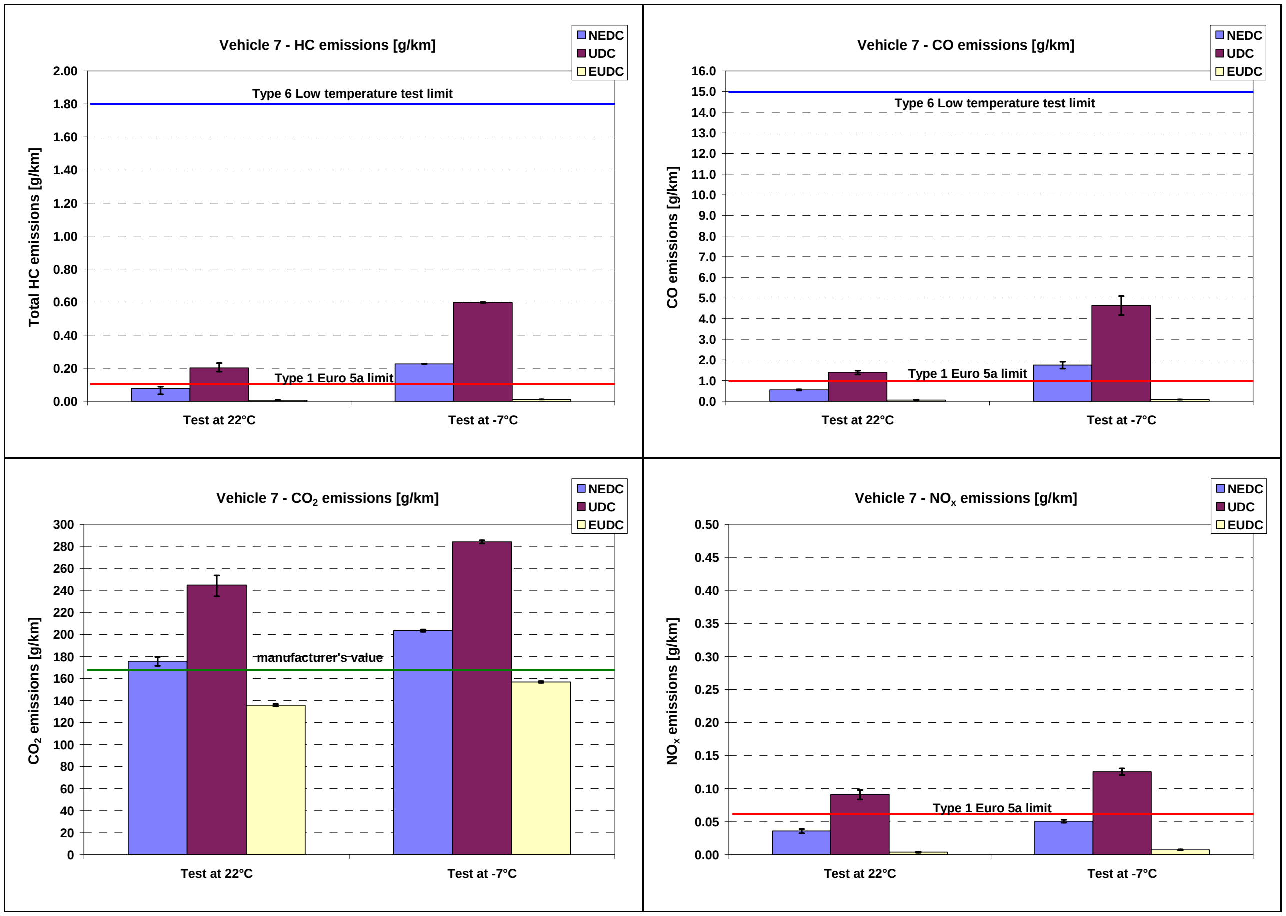


Figure 28 – Vehicle 7: Total HC, CO, CO_2 and NO_x bag emission values measured at 22°C and -7°C over the NEDC, UDC and EUDC driving cycles.

Figure 29 shows the instantaneous gaseous emission for HC, CO, NO_x and the lambda value over the NEDC driving cycle at the two test temperatures. Concerning the total HC emissions their peak concentration increased more than two times over the first cold start seconds of the cycle at -7°C. On the other hand there was not any increase at the absolute value of the maximum concentration of CO at -7°C. The main characteristic for both pollutants behaviour over time was the prolonged warming period of the catalyst at low ambient temperature, which increased from 50 s to 200 s. After this period the catalyst fully oxidized the pollutants resulting in almost zero CO and total HC concentration.

The majority of NO_x was also emitted during the cold start phase. Over the rest of the cycle NO_x emissions remained low, as the vehicle ran on stoichiometric air to fuel ratio.

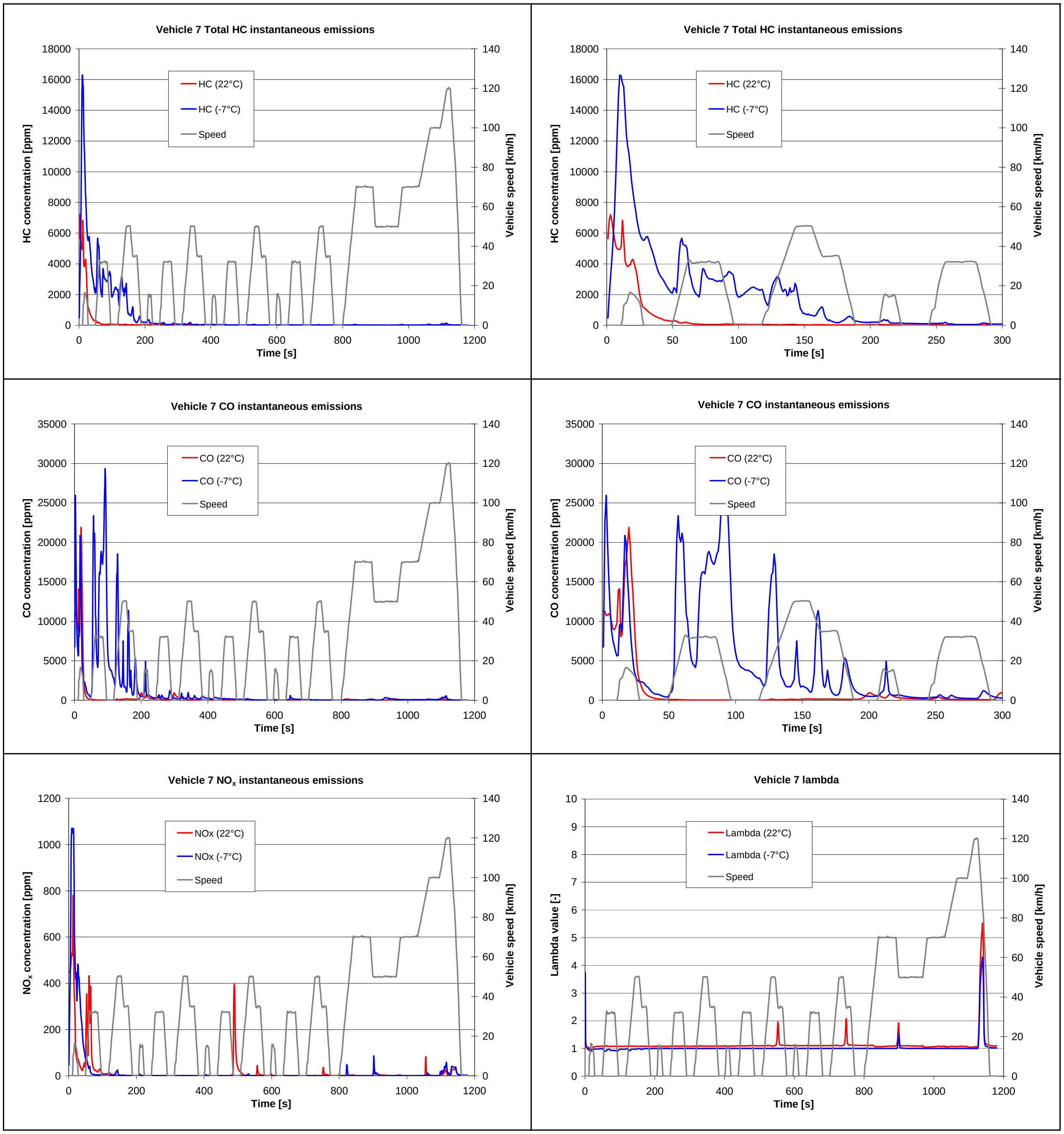


Figure 29 – Vehicle 7: Total HC, CO and NO_x instantaneous emissions and lambda value over the NEDC driving cycle at 22°C and -7°C.

Figure 30 shows the cumulative mass emissions of HC, CO and NO_x over the NEDC cycle in both low and ambient temperature test.

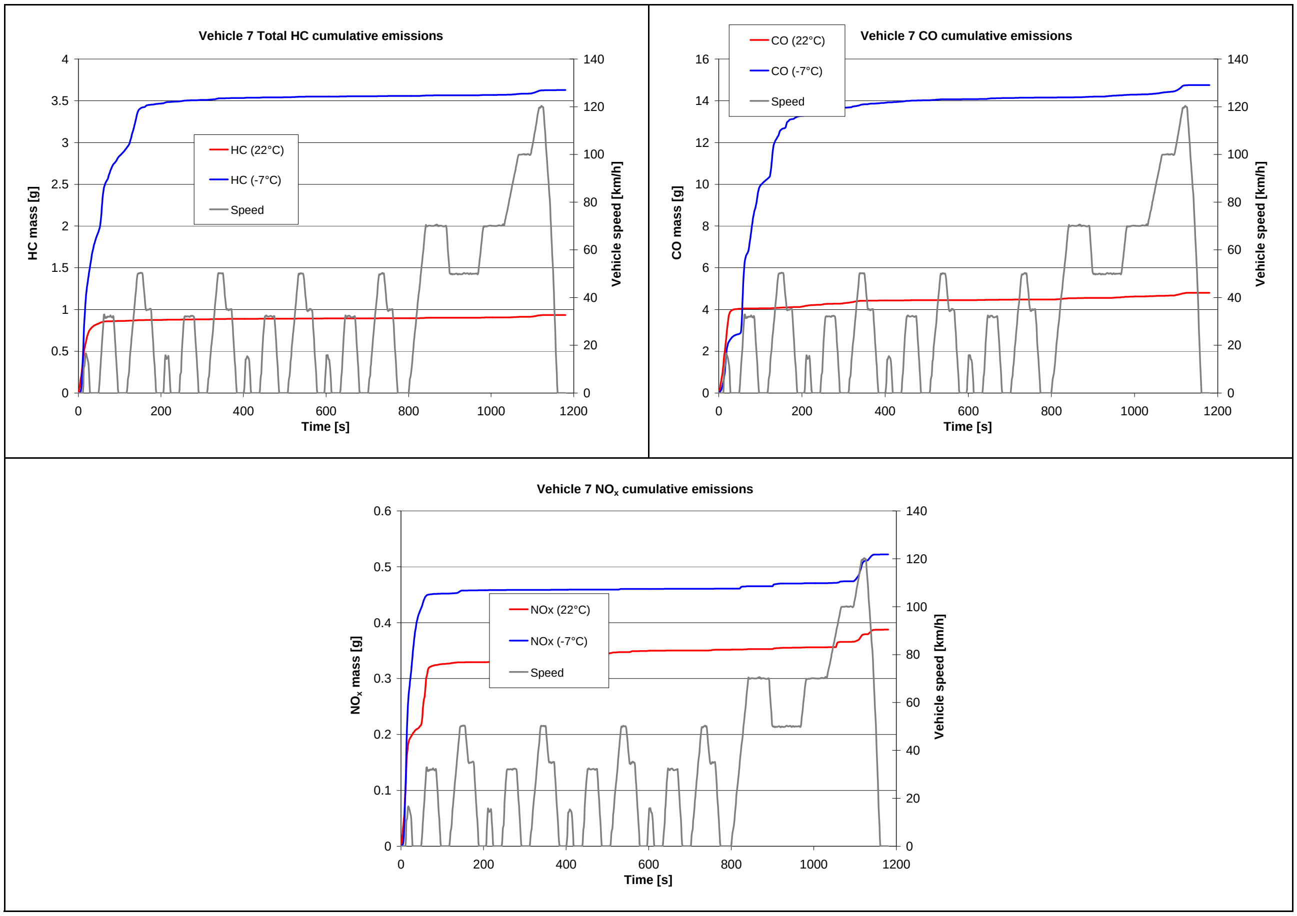


Figure 30 – Vehicle 7: Total HC, CO and NO_x cumulative mass emissions over the NEDC driving cycle at 22°C and -7°C.

VEHICLE 8

Table 18 provides the average bag emission values and fuel consumption for Vehicle 8 over NEDC (22°C) and over the urban part of the cycle UDC (22°C and -7°C).

Table 18 – Measured gaseous emissions and fuel consumption for Vehicle 8 over the NEDC (22°C) and UDC (22°C & -7°C) driving cycles (in parentheses the type approval data).

VEHICLE 8				
Emissions	**Unit**	**NEDC 22°C**	**UDC 22°C**	**UDC -7°C**
HC	g/km	0.101 (0.050)	0.274	0.957 (1.270)
CO	g/km	0.402 (0.320)	1.085	6.694 (3.580)
NO_x	g/km	0.009 (0.0)	0.024	0.203
CO_2	g/km	257.8 (261)	382.0 (388)	480.3
Fuel Consumption	l/100km	10.9 (11.1)	16.2 (16.5)	20.8

Figure 31 shows the bag gaseous emission values for total HC, CO, CO_2 and NO_x at 22°C and -7°C measured over the NEDC, UDC and EUDC driving cycles. In the plots the Euro 4 limits for CO, total HC and NO_x (1, 0.1 and 0.08 g/km respectively) for Type I test (Category M – Passenger Vehicles) over the NEDC cycle are indicated by a red solid line. The Type VI low temperature test limits for CO and total HC (15 and 1.8 g/km respectively) are indicated by a blue solid line. The manufacturer's CO_2 emission value (261 g/km) over the NEDC cycle is indicated in the respective chart by a green solid line. The scale of CO_2 emission bar chart reaches 500 g/km, different for the other reported vehicles, due to the increased CO_2 emissions of Vehicle 8.

The total HC measured at JRC for this vehicle were exactly in line with the Euro 4 respective limit of 0.1 g/km. CO measured emission was greater than the type approval data in both the tests (22 and -7°C). NO_x emissions were almost 10 time below the Euro 4 limit of 0.08 g/km, while the respective type approval value was zero. CO, total HC and NO_x emissions over the NEDC increased by 6.1, 3.5 and 8.1 times respectively when the test carried out at low ambient temperature test (-7°C). CO_2 emission and fuel consumption at 22°C was smaller than the respective type approval values. At -7°C the CO_2 over the NEDC increased by 20%, compared to the respective value at 22°C.

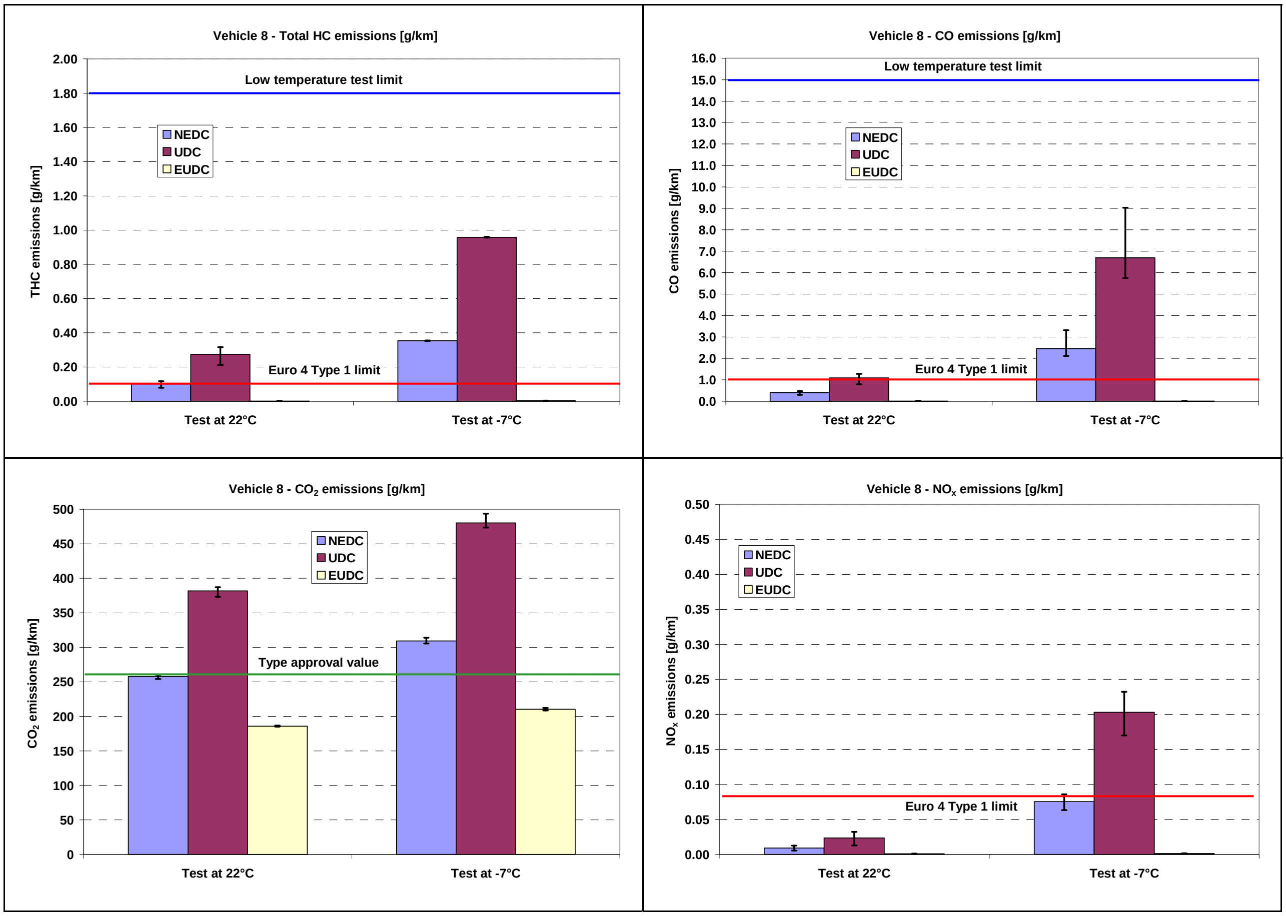


Figure 31 – Vehicle 8: Total HC, CO, CO_2 and NO_x bag emission values measured at 22°C and -7°C over the NEDC, UDC and EUDC driving cycles.

Figure 32 shows the instantaneous gaseous emission for CO, NO_x and the lambda value over the NEDC driving cycle at the two test temperatures. Instantaneous HC emissions were not available for the specific vehicle due to a problem to the respective analyzer. CO concentration at -7°C was increased compared to the respective one at 22°C, while the prolonged warming of the catalyst was evident, reaching the first 150 s of the cycle. After the specific time instant the CO was fully oxidized passing through the three-way catalytic converter of the vehicle.

Similar behaviour exhibited the NO_x tail-pipe concentration. At low ambient temperature the concentration was increased also during the warming of the catalyst. After the first 100 s of the cycle NO_x emissions remained to very low limits, even during the extra-urban part of the cycle. Lambda value calculated from instantaneous emissions reached 0.8 at -7°C and remained below one for longer period than at 22°C test, due to the intense enrichment of the air to fuel ratio.

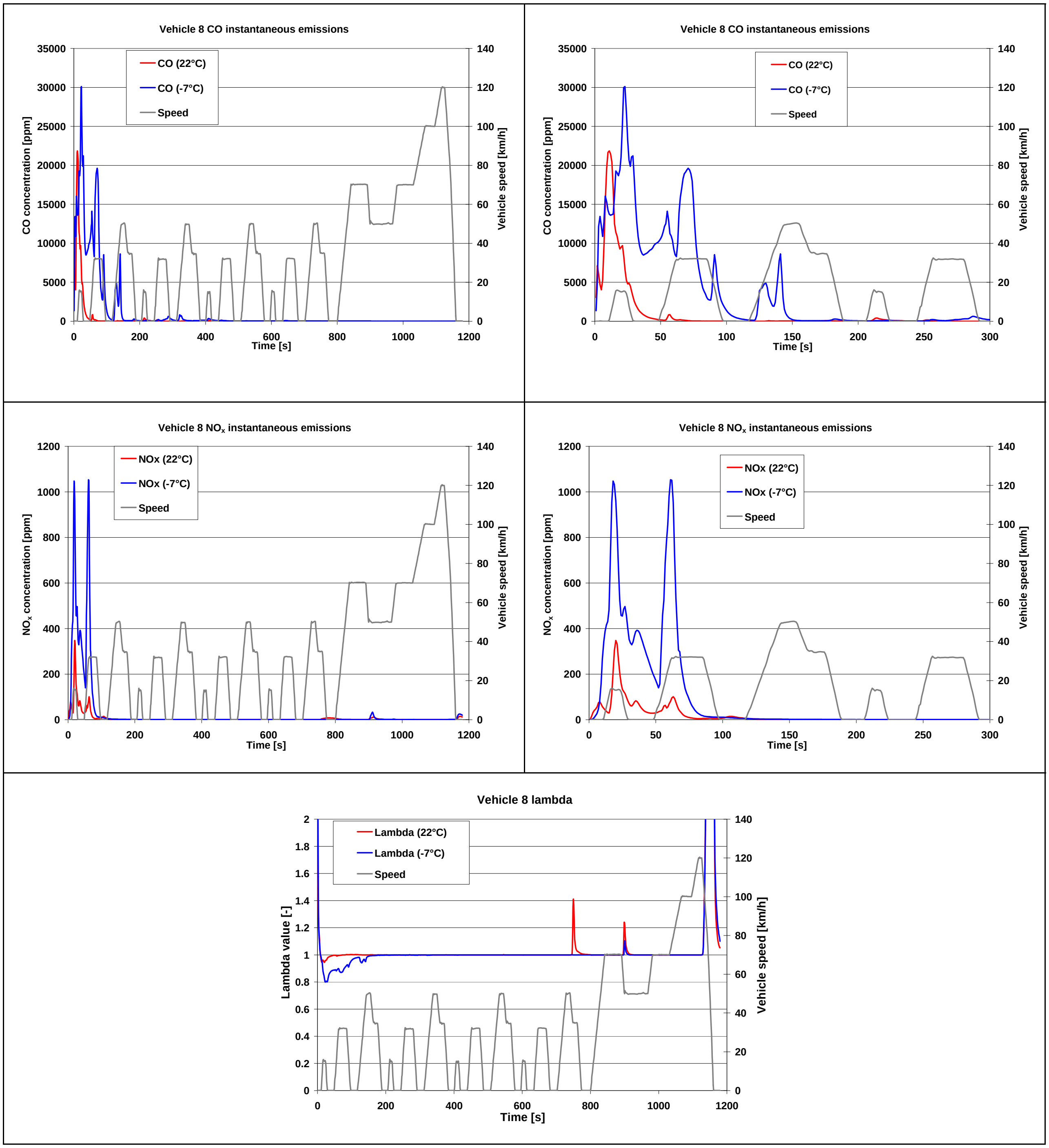


Figure 32 – Vehicle 8: CO and NO_x instantaneous emissions and lambda value over the NEDC driving cycle at 22°C and -7°C.

Figure 33 shows the cumulative mass emissions of CO and NO_x over the NEDC cycle in both low and ambient temperature test. Their behaviour was identical: The majority of each pollutant mass was emitted during the warming period of the catalyst substrate. At -7°C the quantity of each pollutant was increased several times, as already mentioned above.

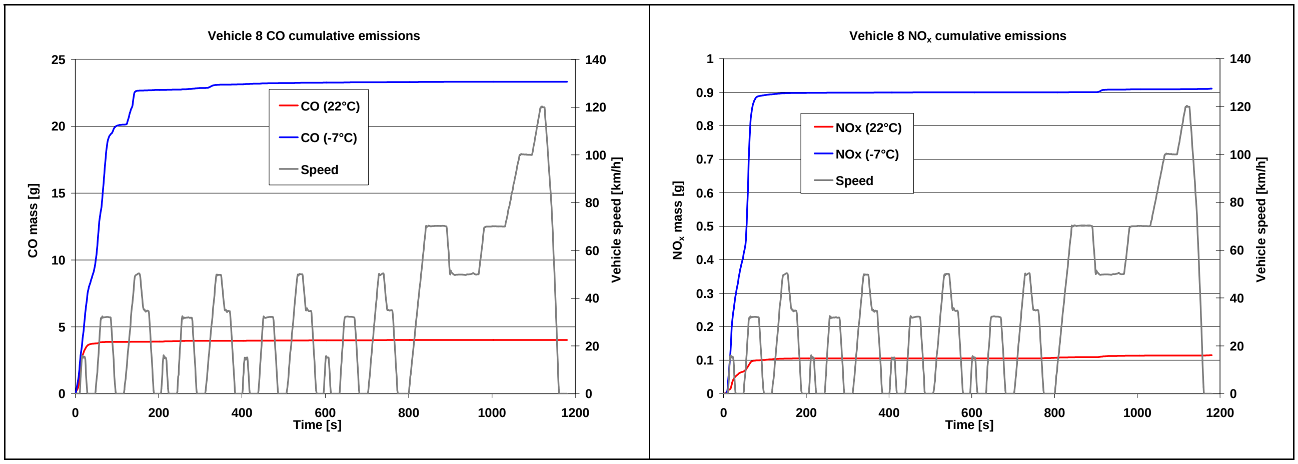


Figure 33 – Vehicle 8: CO and NO_x cumulative mass emissions over the NEDC driving cycle at 22°C and -7°C.

VEHICLE 9

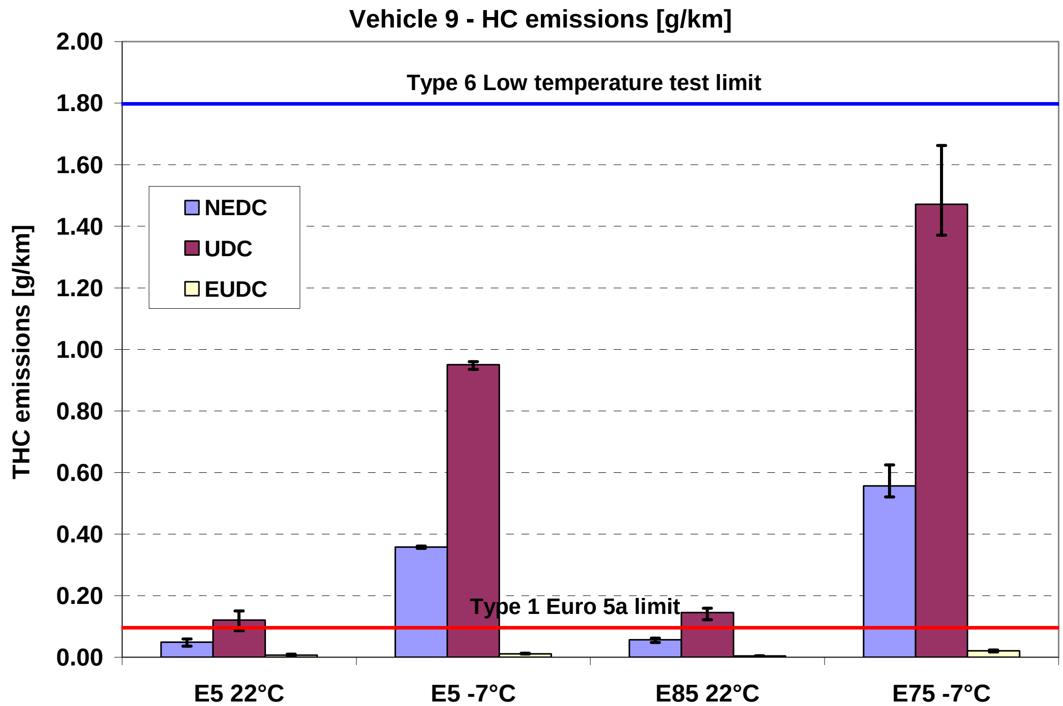
Vehicle 9 is the first of the two Ethanol Flex-Fuel reported vehicles. Table 19 provides the mean bag gaseous emission values and the fuel consumption over the NEDC (22°C) and the UDC (22°C & -7°C) cycles for Vehicle 9. At 22°C results of both fuels E5 and E85 are presented, as well as at -7°C results of fuels E5 and E75. The type approval values for total HC, CO, NO_x (NEDC 22°C), and for CO_2 and fuel consumption values (NEDC and UDC at 22°C) are given in parentheses. The Type VI type approval values for CO and total HC were not available.

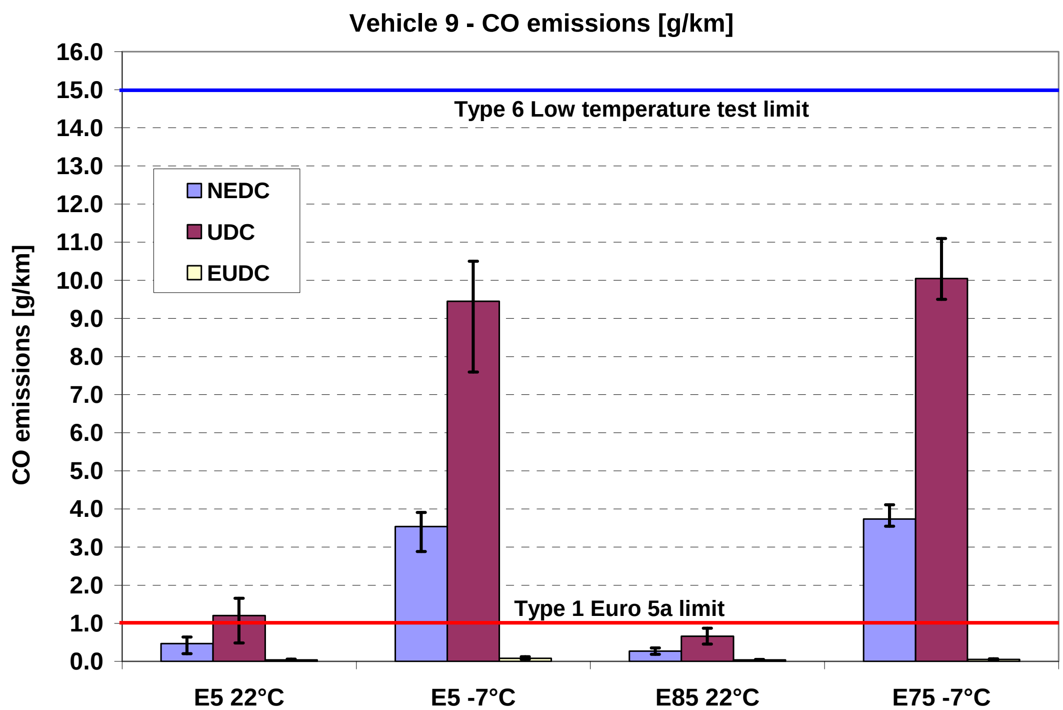
The CO_2 and fuel consumption values measured in JRC increased compared to the respective type approval values, which could be attributed to the fact that the “Start-Stop” system of the specific vehicle was disabled during the measurement campaign.

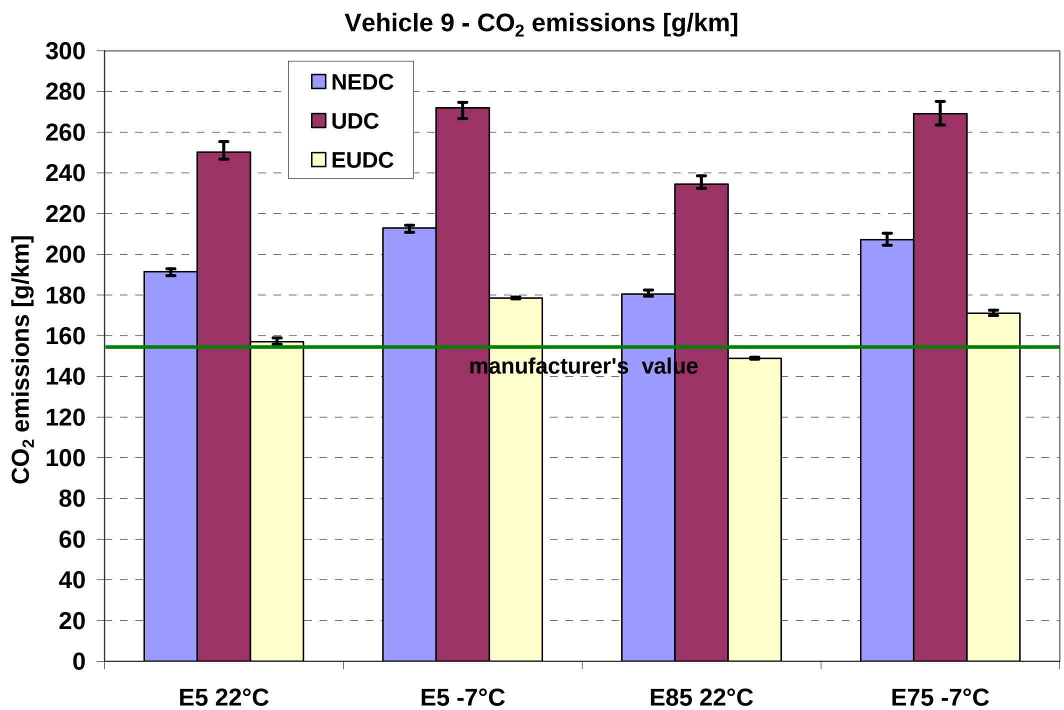
Table 19 – Measured gaseous emissions and fuel consumption for the Vehicle 9 over the NEDC (22°C) and UDC (22°C & -7°C) driving cycles (in parentheses the type approval values).

VEHICLE 9							
Emissions	**Unit**	**NEDC 22°C**		**UDC 22°C**		**UDC -7°C**	
		E5	**E85**	**E5**	**E85**	**E5**	**E75**
HC	g/km	0.049 (0.028)	0.057 (0.082)	0.120	0.145	0.951	1.471
CO	g/km	0.471 (0.239)	0.268 (0.341)	1.203	0.660	9.452	10.045
NO_x	g/km	0.026 (0.054)	0.011 (0.017)	0.032	0.019	0.064	0.032
CO_2	g/km	191.5 (154)	180.5 (154)	250.2 (195)	234.5 (208)	271.9	269.0
Fuel Consumption	l/100km	8.3 (6.6)	10.9 (9.2)	10.9 (8.4)	14.3 (12.6)	12.5	16.6

Figure 34 shows the gaseous emission values in bar chart format for both the test temperatures over the NEDC, UDC and EUDC driving cycles. When the vehicle was tested with the high ethanol content fuel E85 at 22°C, total HC slightly increased comparing to the fuel E5, while CO and NO_x emissions decreased. At -7°C, total HC emissions increased 55% (from 0.951 g/km to 1.471 g/km over the UDC running on E5 and E75 fuel respectively), remaining below the current Euro 5a Type VI limit of 1.8 g/km. CO emissions at -7°C slightly increased when using the E75 ethanol fuel, while the NO_x emissions again decreased up to 50% (from 0.064 g/km to 0.032 g/km) over the UDC at -7°C.


Vehicle 9 - HC emissions [g/km]
THC emissions [g/km]
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Type 6 Low temperature test limit
Type 1 Euro 5a limit
NEDC
UDC
EUDC
E5 22°C
E5 -7°C
E85 22°C
E75 -7°C


Vehicle 9 - CO emissions [g/km]
CO emissions [g/km]
16.0
15.0
14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Type 6 Low temperature test limit
Type 1 Euro 5a limit
NEDC
UDC
EUDC
E5 22°C
E5 -7°C
E85 22°C
E75 -7°C



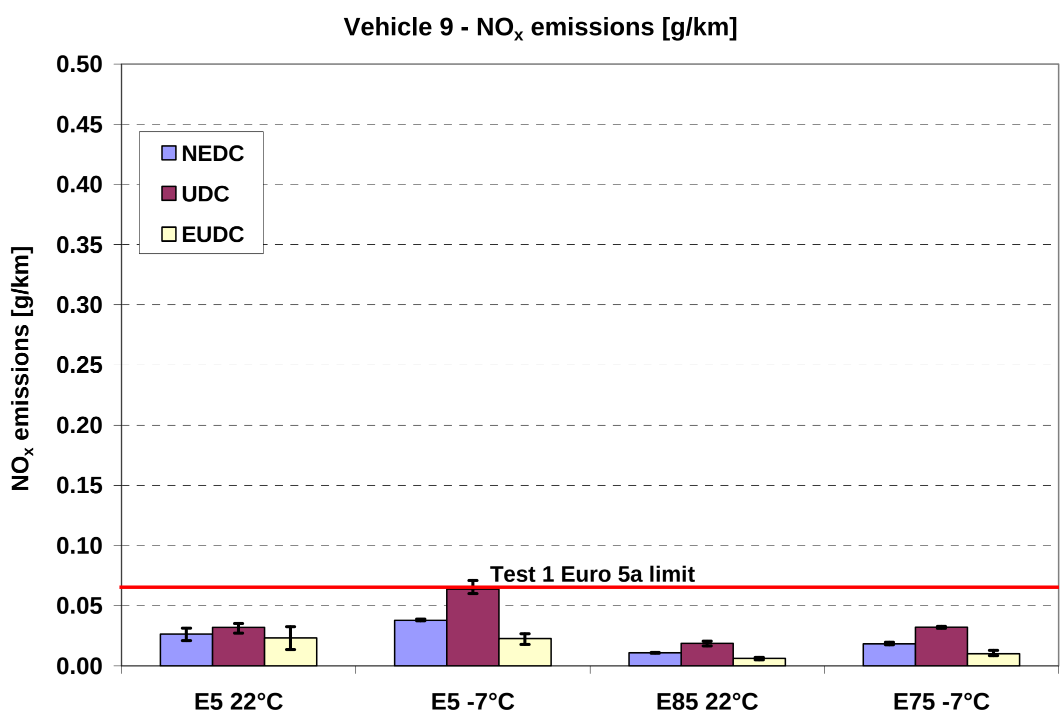


Figure 34 – Vehicle 9: Total HC, CO, CO_2 and NO_x emission measurements at 22°C and -7°C over the NEDC, UDC and EUDC driving cycles for fuels E5, E85 (22°C) and E5, E75 (-7°C).

Figure 35 shows the instantaneous gaseous emission for HC, CO, NO_x and the lambda value over the NEDC driving cycle at 22°C (for fuels E5 and E85) and at -7°C (for fuels E5 and E75).

The warming period of the catalyst increased at low temperature test, regardless the ethanol content of the fuel.

NO_x emissions were emitted during the cold start phase and some picks up to 150 ppm over the extra-urban part of the cycle. Apart from the cold start period, NO_x concentration pattern was the same over the duration of the cycle, regardless the used fuel or the test temperature, as the engine ran on stoichiometric air to fuel ratio mode.

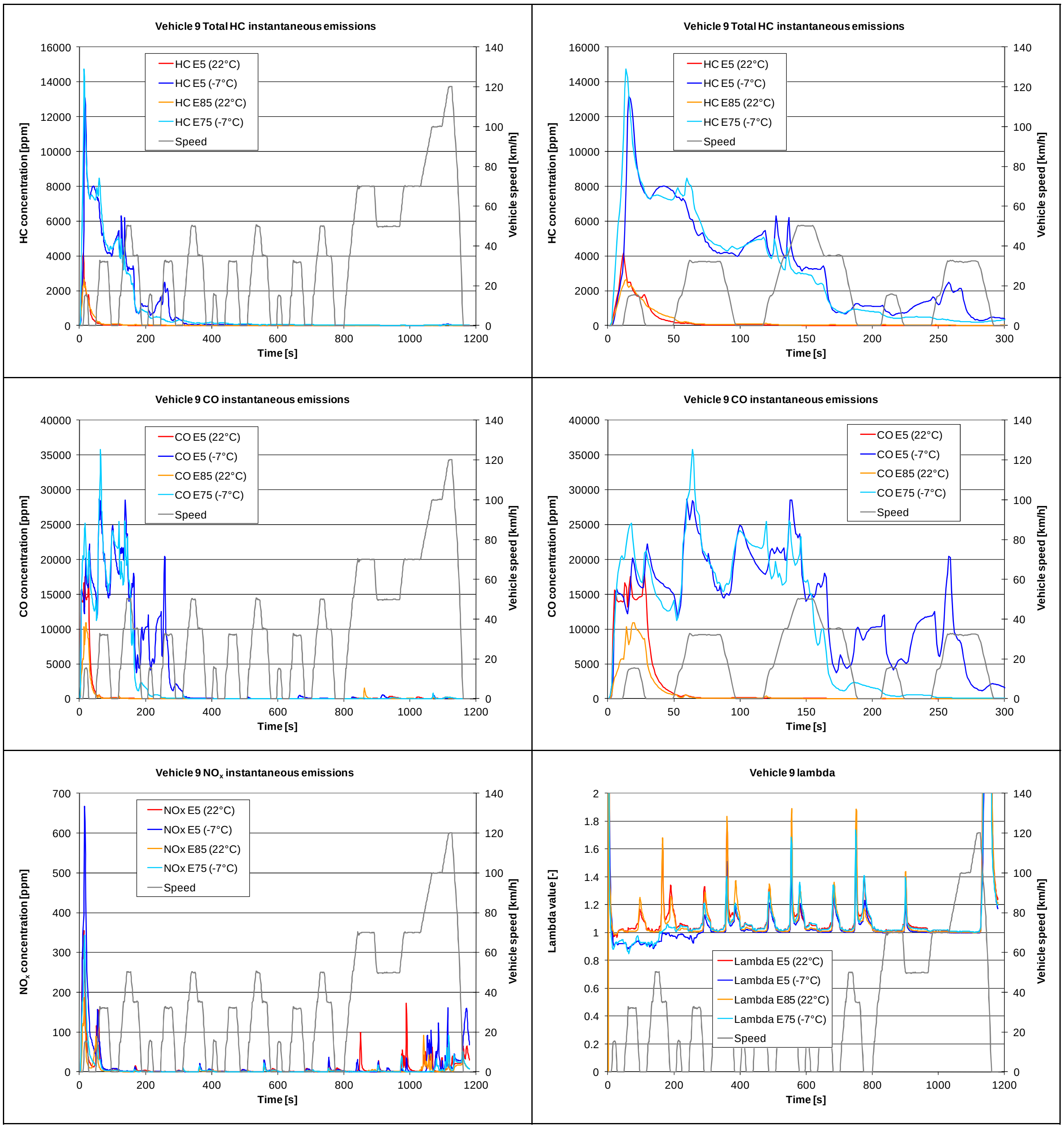


Figure 35 – Vehicle 9: Total HC, CO and NO_x instantaneous emissions and lambda value over the NEDC driving cycles for fuels E5, E85 (22°C) and E5, E75 (-7°C).

Figure 36 shows the cumulative mass emissions of HC, CO and NO_x over the NEDC cycle in both low and ambient temperature test. After the warming of the catalyst substrate there was not any slip of CO or HC over the rest duration of the cycle. NO_x mass cumulative emissions increased over the high speed-load extra-urban part of the cycle, as it has already mentioned in Figure 35.

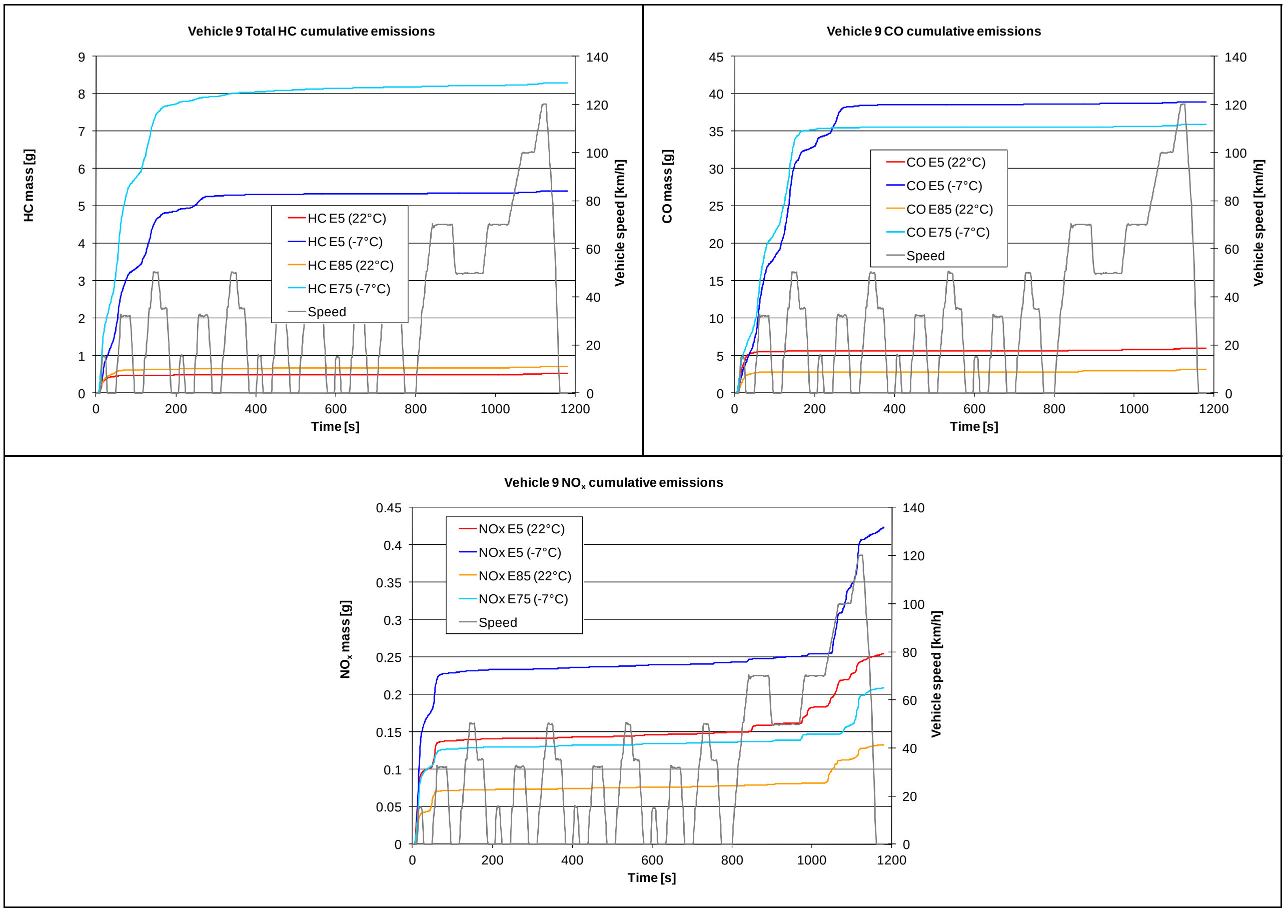


Figure 36 – Vehicle 9: Total HC, CO and NO_x cumulative mass emissions over the NEDC driving cycle for fuels E5, E85 (22°C) and E5, E75 (-7°C).

VEHICLE 10

Table 20 provides the bag gaseous emissions and the fuel consumption measured over the NEDC (22°C) and UDC (22°C & -7°C) cycles for Vehicle 10, the Euro 4 certified Ethanol Flex Fuel vehicle. The values in the parentheses refer to the type approval values for each pollutant and the manufacturer's CO_2 emission and fuel consumption. Furthermore, these values have been derived with the reference fuel without Ethanol content E0 for vehicles certified as Euro 4 emission standards.

CO_2 emissions measured at JRC were very close to the manufacturer's values, while the pollutants emissions for total HC, CO and NO_x increased, comparing to type approval respective values.

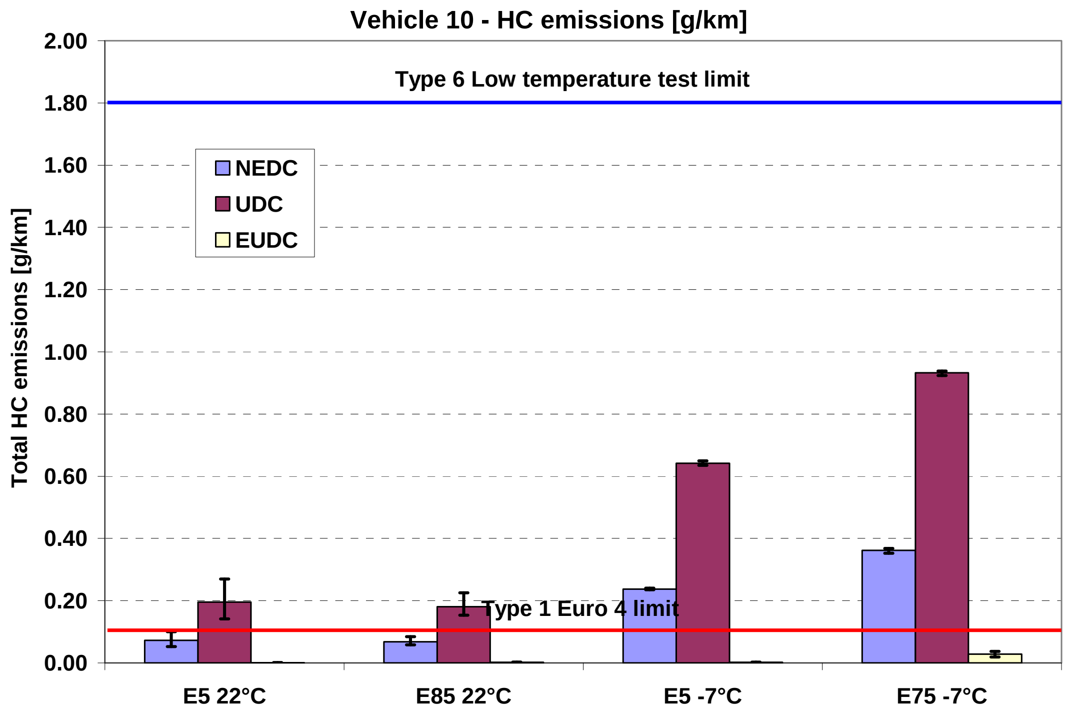
Table 20 – Measured gaseous emissions and fuel consumption for the Vehicle 10 over the NEDC (22°C) and UDC (22°C & -7°C) driving cycles (in parentheses the type approval values measured in reference fuel E0 of Euro 4 vehicles).

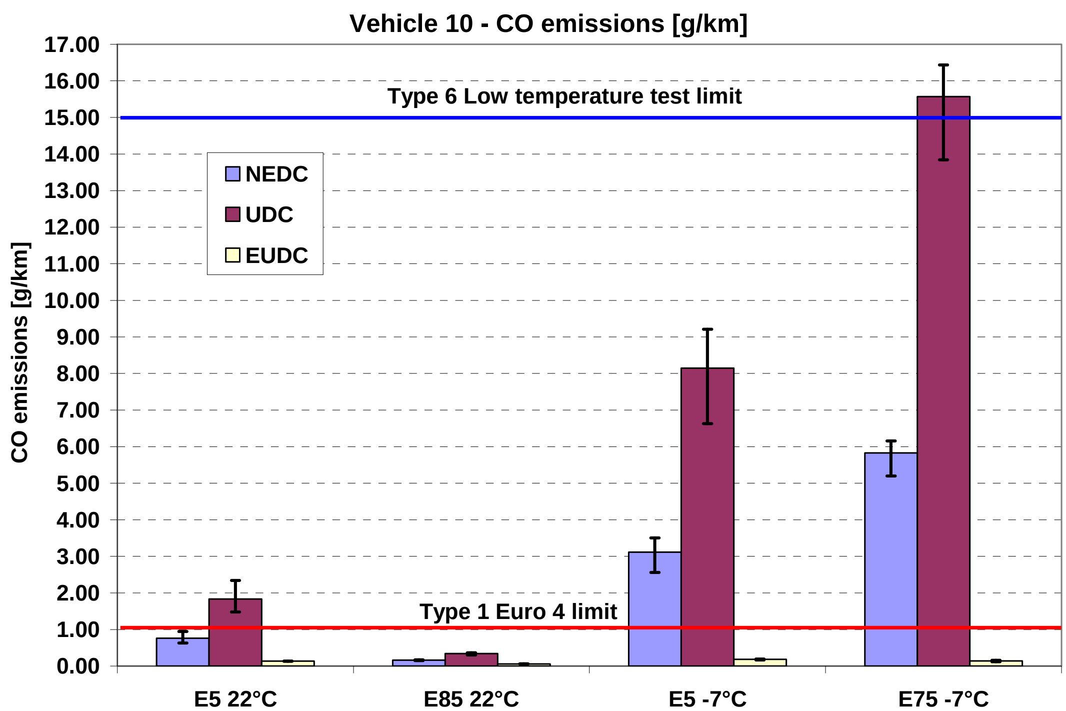
VEHICLE 10							
Emissions	**Unit**	**NEDC 22°C**		**UDC 22°C**		**UDC -7°C**	
		E5	**E85**	**E5**	**E85**	**E5**	**E75**
HC	g/km	0.073 (0.042 E0)	0.068	0.196	0.181	0.642	0.932
CO	g/km	0.761 (0.396 E0)	0.163	1.832	0.342	8.146	15.568
NO_x	g/km	0.027 (0.019 E0)	0.021	0.069	0.049	0.112	0.102
CO_2	g/km	174.2 (177 E0)	166.7	242.3 (244 E0)	234.9	291.4	283.1
Fuel Consumption	l/100km	7.6 (7.4 E0)	10.1	10.7 (10.3 E0)	14.3	13.2	17.9

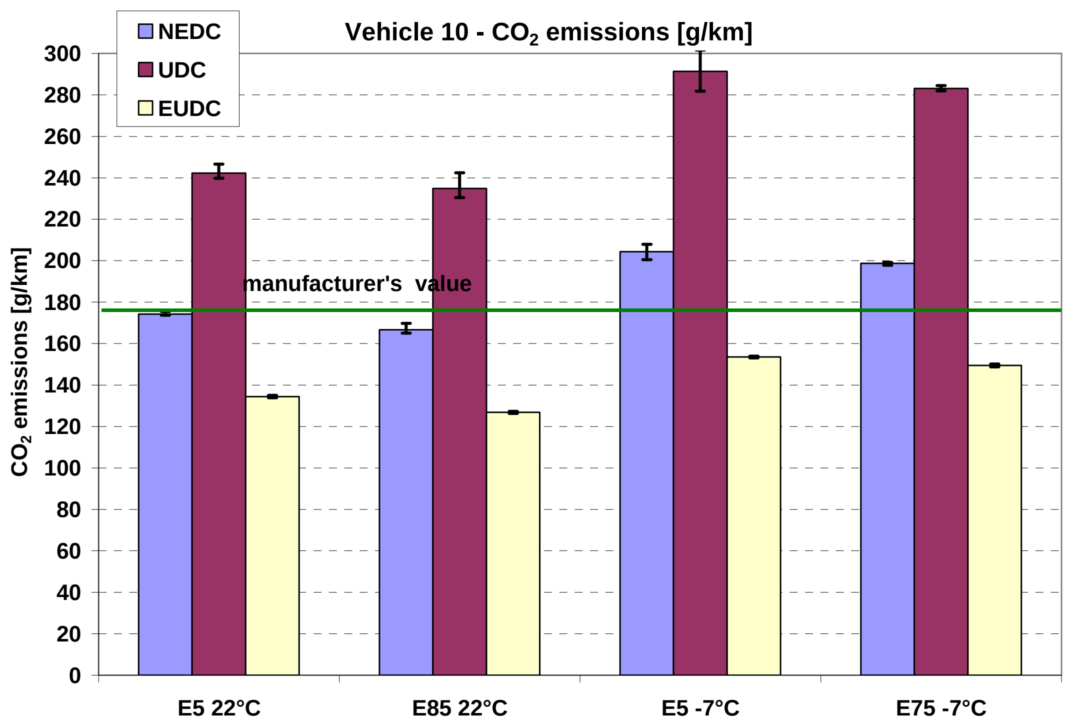
Figure 37 shows the bag gaseous emission values of Vehicle 10 measured over the NEDC, UDC and EUDC driving cycles at 22 °C and -7°C in bar chart format. The Euro 4 Type I and Type VI test limits are also in this case presented in red and blue solid lines respectively, while the manufacturer's CO_2 emissions for Type I test at 22°C with E0 fuel (177 g/km) is shown in green solid line in the respective chart. At 22°C the CO emissions decreased when the vehicle was tested with the E85 high ethanol content fuel, while at -7°C the CO emissions got double with E75 fuel, compared to the emissions at -7°C with the E5 fuel. Furthermore, the vehicle did not comply with Type VI low temperature test limits when running on the high ethanol content

E75 fuel. It is worthwhile to mention that Vehicle 10 was certified as Euro 4, consequently, it was not supposed to comply with Type VI test limits with the high ethanol content fuel.

Total HC emissions also increased at low temperature regardless the used fuel, but in any case they stayed below 0.642 g/km (E5) and 0.932 g/km (E75) over the UDC, when the respective legislated Type VI limit is 1.8 g/km.




Vehicle 10 - CO emissions [g/km]
CO emissions [g/km]
17.00
16.00
15.00
14.00
13.00
12.00
11.00
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Type 6 Low temperature test limit
Type 1 Euro 4 limit
NEDC
UDC
EUDC
E5 22°C
E85 22°C
E5 -7°C
E75 -7°C


Vehicle 10 - CO_2 emissions [g/km]
CO_2 emissions [g/km]
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
manufacturer's value
NEDC
UDC
EUDC
E5 22°C
E85 22°C
E5 -7°C
E75 -7°C

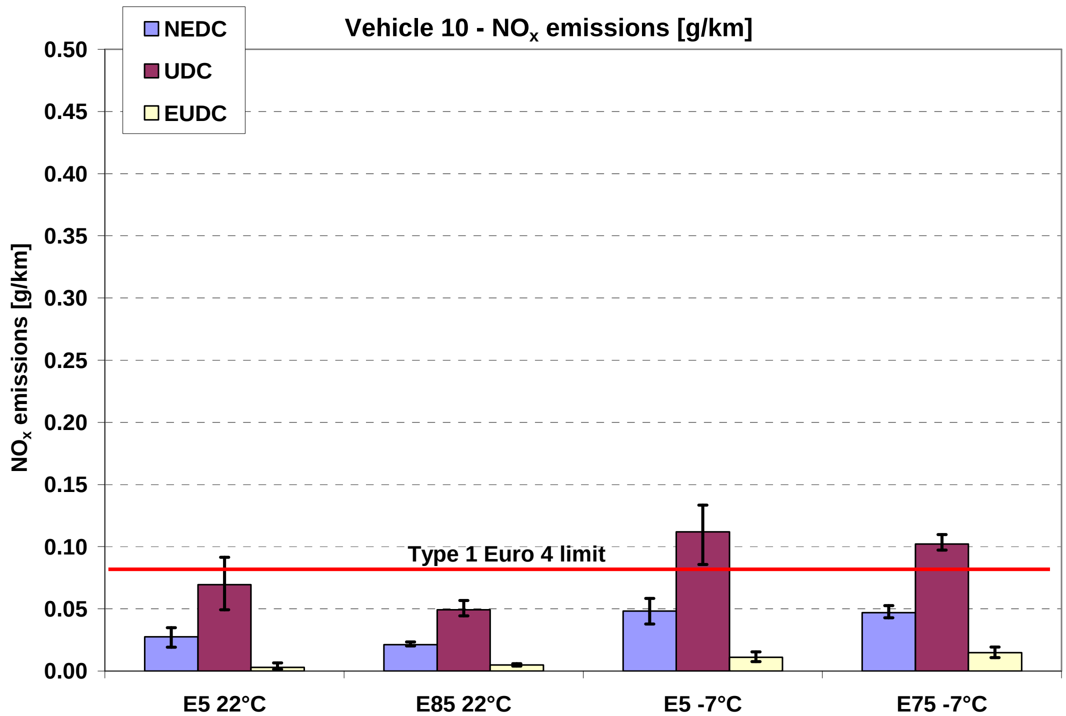


Figure 37 – Vehicle 10: Total HC, CO, CO_2 and NO_x emission measurements at 22°C and -7°C over the NEDC, UDC and EUDC driving cycles for fuels E5, E85 (22°C) and E5, E75 (-7°C).

Modal second by second emissions data were not available for Vehicle 10, due to a problem to the analyzers.

5.6 OVERVIEW OF THE TESTS CARRIED OUT AT THE JRC

In this section the overall results of the tested vehicles are presented and compared. The results refer to cold start CO and total HC emissions in low ambient temperature test (-7°C) over the UDC driving cycle (Type VI test). Moreover, the emissions of the vehicles tested at the JRC are compared to the type approval data. NO_x emission results are also presented for the tested vehicles at both temperatures (22°C and -7°C).

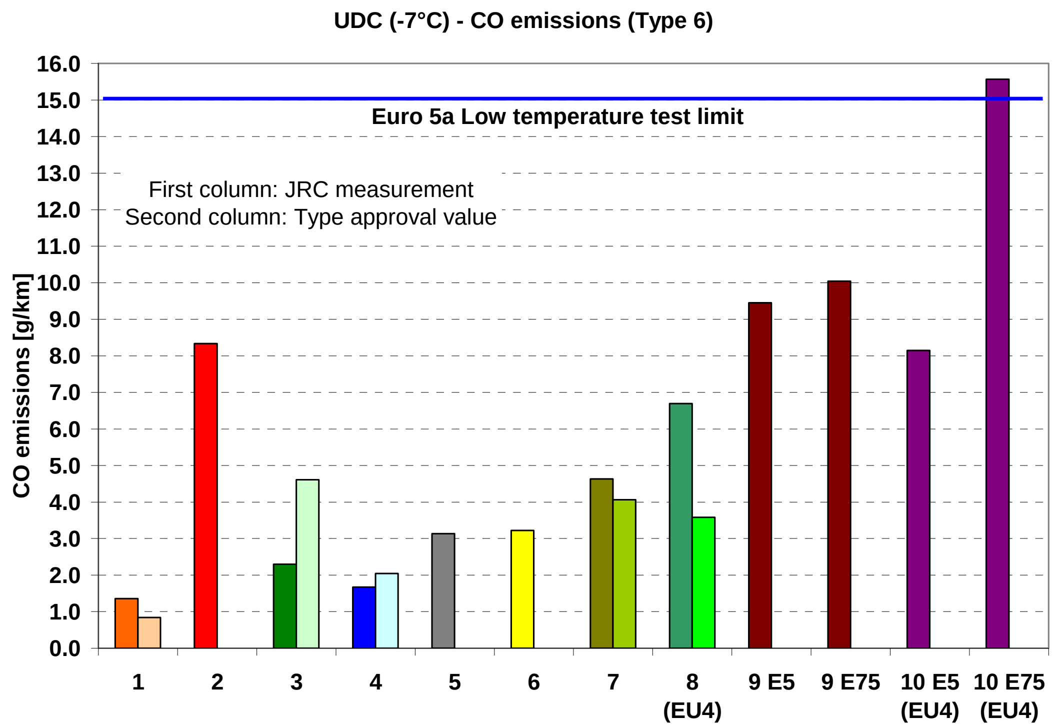
Figure 38 presents the results of low temperature emission test (Type VI) in bar chart format. Where available, also the CO and total HC type approval data for the same model are shown (second column for each vehicle). CO and total HC are the only pollutants currently regulated at low temperature and in this case the emissions values are referred to the UDC driving cycle. The results are also presented in X-Y scatter chart. In the latter, in addition to the current legislative limits (15 and 1.8 g/km for CO and total HC respectively), dashed lines of different colours indicate the emission values corresponding to the 90^{th}, 70^{th} and 50^{th} percentiles of the type approval data of Euro 5a petrol engines published by KBA and calculated as described in paragraph 4.3 of this report.

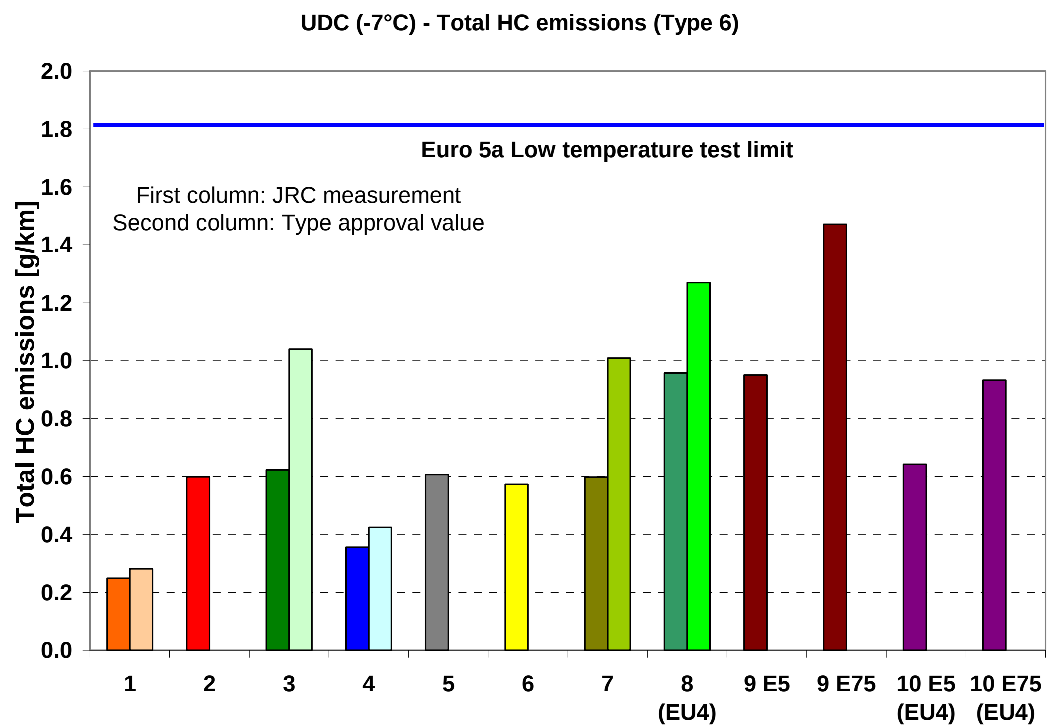
It is worthwhile to mention that the percentile values represented by the dashed lines have been calculated for each pollutant separately. This means that an engine that emits less than 5.6 g/km of CO (corresponding to the 90^{th} percentile of the total 227 Euro 5a examined engines) does not necessarily emit less than 1.43 g/km of total HC. For this reason the percentage of Euro 5a engines has been also calculated which corresponds to engines that emit simultaneously less than the value of 5.6 g/km for CO and 1.43 g/km for total HC. In this case the engines that comply simultaneously with these limits correspond to 81.5% of all the 227 Euro 5a examined engines. The percentage of the engines that comply simultaneously with the limits of 3.8 and 1.16 g/km for CO and total HC has been also calculated (corresponding to the 70^{th} percentile of the engines that emit less than these two limits separately). In this case 52.4% of the Euro 5a engines belong within these two limits simultaneously. Finally, 30.8% of the examined Euro 5a engines emit less than 3 and 1.01 g/km simultaneously, when the percentile for each pollutant separately is 50%.

All the mono fuel vehicles tested at the JRC (Vehicle 1 to 8), with the exception of the CO value of the Vehicle 2 and Vehicle 8 (EU4), were within the values corresponding to the 90^{th} percentile which means 5.6 g/km and 1.43 g/km for CO and total HC respectively (or corresponding to the 81.5^{th} percentile for both pollutants simultaneously). Moreover, all the mono fuel vehicles with the exception of Vehicles 2, 7 and 8 (EU4) were below 3.8 g/km and 1.16 g/km for CO and total HC, which correspond to the 70^{th} percentile of the Euro 5a gasoline engines calculated from the KBA data set (or corresponding to the 52.4^{th} percentile for both pollutants simultaneously). Vehicle 1 showed the best performance in the Type VI test according to the JRC measurements.

Type approval Type VI test data were available for five vehicles (1, 3, 4, 7and 8 (EU4)). For Vehicles 1 and 4 the measured at JRC emissions were close to type approval data. For Vehicles 3 7 and 8(EU4) the total HC emissions measured at JRC were in general lower than type approval data.

In Figure 38 the Type VI test emission performance of flex fuel vehicles is also presented. In general, these vehicles exhibited inferior CO and total HC performance compared to the mono fuel Euro 5a vehicles, even when the low ethanol content E5 fuel was used. When the fuel E75 was used both CO and total HC emissions increased (6-91%). Euro 4 Vehicle 10 is the only one which does not comply with the CO Type VI limits, when running on E75 fuel. In general, apart from this case, CO emissions of flex fuel vehicles were below 10.1 g/km, while total HC emissions remained in all cases below 1.48 g/km over the UDC driving cycle at -7°C. These results concern only the two examined vehicles, which only one was certified as Euro 5.





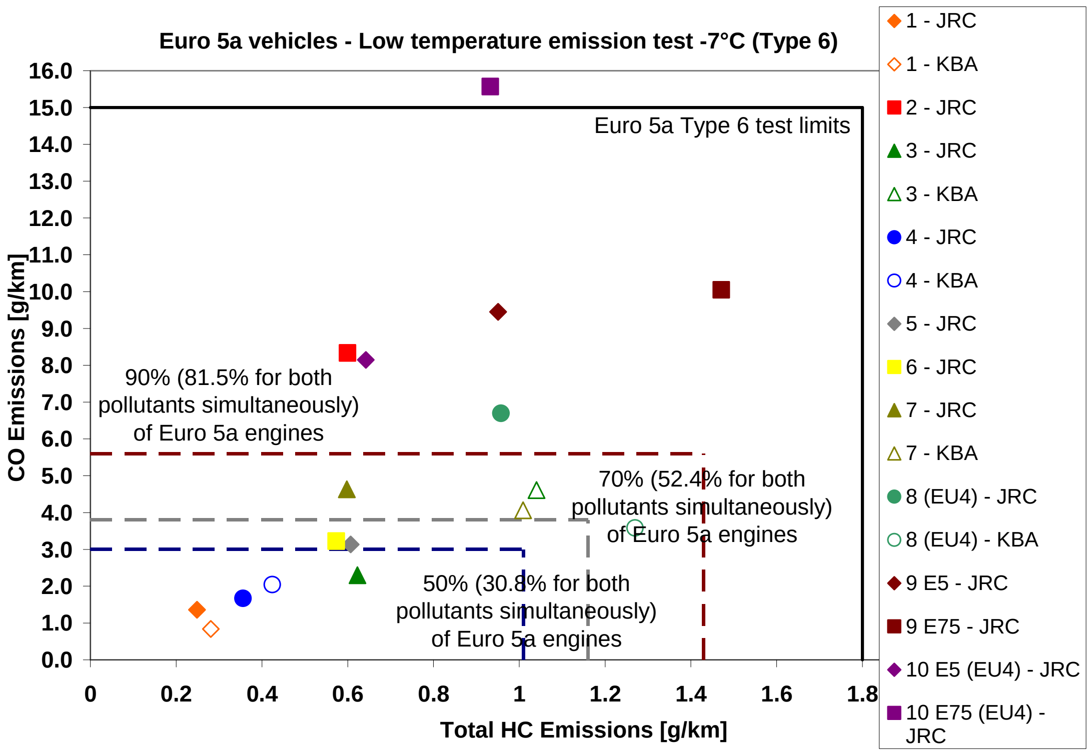
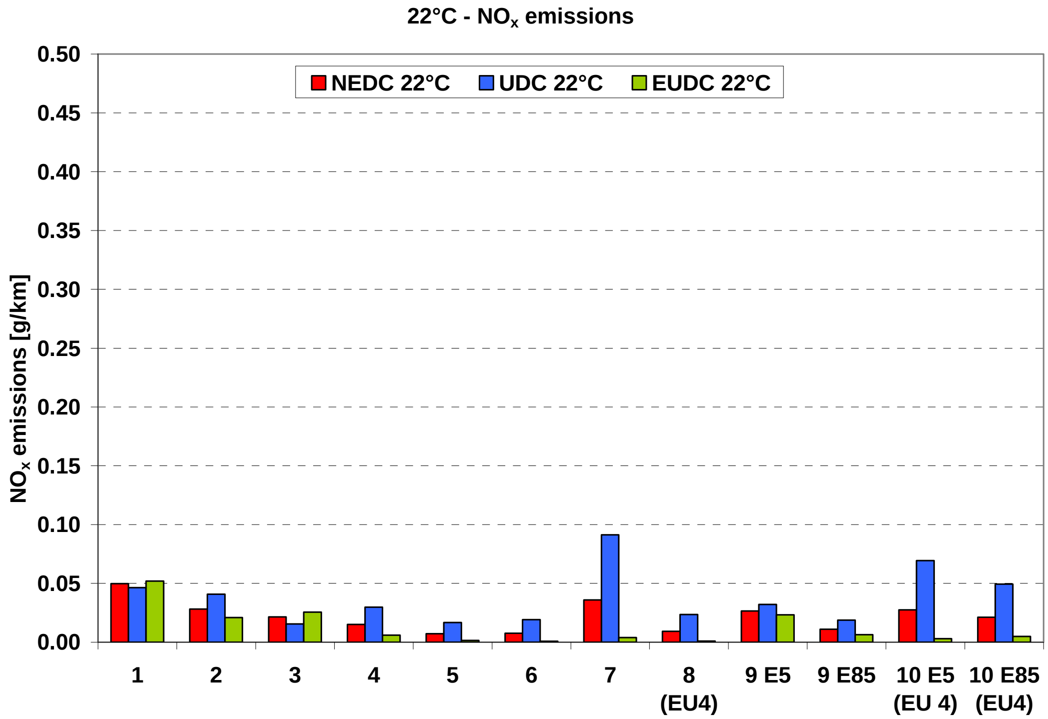


Figure 38 – Total HC and CO bag emission values over the UDC driving cycle at -7°C (Type 6 test) for the tested vehicles.

Figure 39 shows the NO_x emission performance measured over the NEDC, UDC and EUDC for both test temperatures in bar chart format. For clarity the scale in the plots is common for both test temperatures.

NO_x emission performances in the low ambient temperature test are not so obvious and predictable as in general happens for CO and HC. For almost all the mono fuel Euro 5a compliant vehicles (1 to 7) NO_x emission values at -7°C measured over the NEDC cycle increased maximum 3.5 times compared to the values measured at 22°C. The exceptions were Vehicle 5, which turned out to have lower NO_x emissions at -7°C and Vehicle 3 which emitted 8.4 times more NO_x at -7°C than at 22°C. As it has been described in the relevant chapter, this seems due to a very peculiar combustion strategy of Vehicle 3.. Also Vehicle 7 emitted increased NO_x emissions compared to the other mono-fuel vehicles in both temperature tests. All the other mono fuel Euro 5a tested vehicles emitted less than 0.075 g/km of NO_x at -7°C over the UDC cycle. The respective value for Vehicle 3 was 0.464 g/km, almost 6.2 times higher and for Vehicle 7 over the UDC at -7°C 0.126 g/km. Vehicle 8 (EU4) emitted 8 times more NO_x emissions at -7°C, reaching 0.2 g/km over the UDC cycle.

NO_x emissions of flex fuel vehicles were in general in line with the mono fuel ones, at least for Vehicle 9, which was also certified as Euro 5a. Euro 4 Vehicle 10 emitted increased NO_x emissions, even at 22°C test, which was expected, since passing from Euro 4 to Euro 5 emission standards the only gaseous pollutant which limits became stricter was the NO_x (from 0.080 g/km to 0.060 g/km for Type I test). For flex fuel vehicles it is also worthwhile to mention that NO_x emissions at both ambient test temperatures decreased when the high ethanol fuel was used (E85 at 22°C and E75 at -7°C), instead of E5 gasoline fuel.



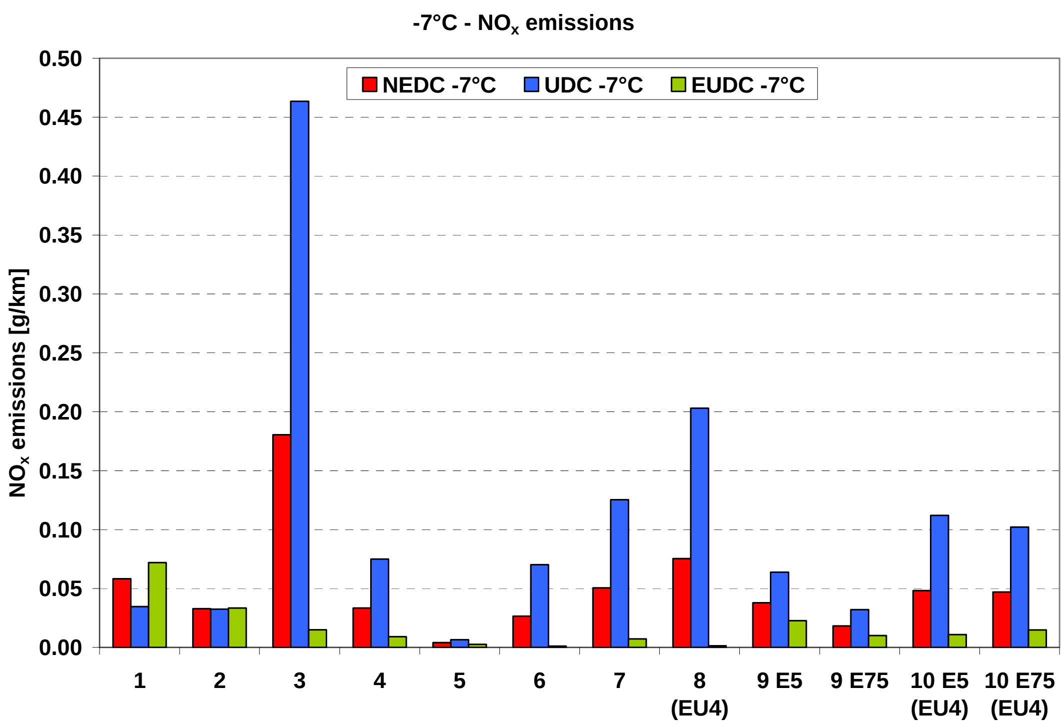


Figure 39 – NO_x bag emission values over the NEDC, UDC and EUDC driving cycles at 22°C and at -7°C for the tested vehicles.

Figure 40 shows the particulate matter PM (over the NEDC cycle) and the particle number PN (over the NEDC, UDC and EUDC cycles) at 22°C and -7°C for the G-DI Vehicle 1 and for the

PFI Vehicle 5. The particle emissions of the G-DI vehicle did not increase significantly when the test was performed at -7°C, while the emissions of the PFI increased by one order of magnitude. PM emissions were below the future Euro 5b legislative limit for both the vehicles. PN emissions of the G-DI vehicle exceeded the Euro 5b legislative limit for diesel vehicles by two orders of magnitude, irrespective of the test temperature. The particle number of the PFI vehicle exceeded the limit only when the test was conducted at -7°C.

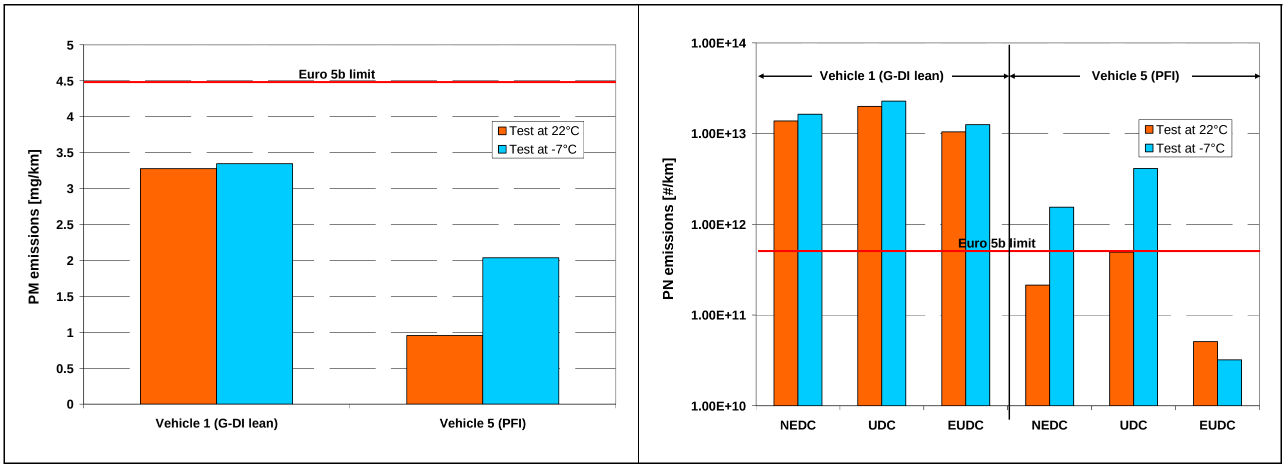


Figure 40 – G-DI vs PFI vehicle: PM emission measurement over the NEDC and PN emission values over the NEDC, UDC and EUDC driving cycles at 22°C and -7°C.

Figure 41 shows the normalized PN instantaneous emissions over the NEDC cycle of the above-mentioned vehicles at both temperatures. The evolution of the emitted particles over the cycle was almost independent of the test temperature, especially in the case of the G-DI vehicle. However, the evolution of PN emissions was strongly dependent of the vehicle's injection system. In the case of the lean G-DI vehicle, the particles were emitted throughout the whole duration of the test cycle. On the contrary, MPI vehicle emitted the majority of the particles over the first seconds of the cycle, while the warming of the engine was taking place. The duration of the "cold" phase of the cycle plays a major role in the particle formation, explaining why the MPI vehicle's emitted particles increased when the test was conducted at low temperature conditions, as was shown before in Figure 40.

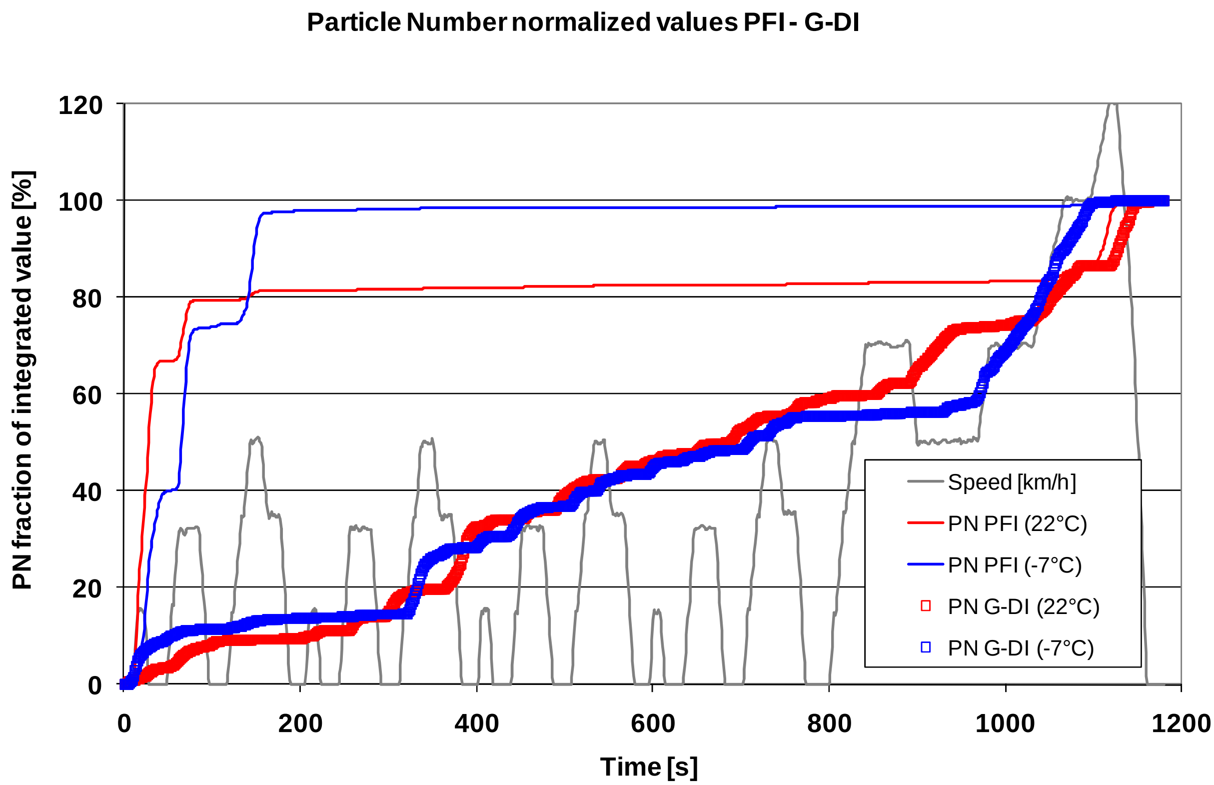


Figure 41 – G-DI vs PFI vehicle: PN normalized emission measurement over the NEDC driving cycle at 22°C and -7°C.

The above mentioned PM-PN results are referred only to these specific vehicles. They might give a trend, but extra testing is needed in order to clarify the dependence of particle emissions of G-DI and PFI vehicles to ambient temperature. An extensive study is currently prepared in JRC addressing the PM/PN emission performance of late technology gasoline light-duty vehicles.

Table 21 provides the overall bag emission values, fuel consumption and PM/PN (where available) results for the vehicles tested at the JRC. The data are provided for the NEDC, UDC and EUDC driving cycles at both temperatures (22°C and -7°C).

Table 21 – Measured bag emission values, fuel consumption and PM//PN emissions (where available) for the tested vehicles over the NEDC, UDC and EUDC driving cycles at 22°C & -7°C.

VEHICLE 1							
Emissions	Unit	NEDC	UDC	EUDC	NEDC	UDC	EUDC
		22°C			-7°C		
HC	g/km	0.043	0.098	0.011	0.098	0.249	0.009
NMHC	g/km	0.033	0.083	0.004	0.087	0.230	0.003
CO	g/km	0.312	0.601	0.143	0.603	1.357	0.163
NO_x	g/km	0.050	0.046	0.052	0.058	0.035	0.072
CO_2	g/km	163.4	205.1	139.1	186.6	259.3	144.2
Fuel Consumption	l/100km	7.0	8.8	6.0	8.0	11.2	6.2
PM	mg/km	3.278	-	-	3.346	-	-
PN	#/km	$1.38x10^{13}$	$2.00x10^{13}$	$1.05x10^{13}$	$1.64x10^{13}$	$2.29x10^{13}$	$1.26x10^{13}$
VEHICLE 2							
Emissions	Unit	NEDC	UDC	EUDC	NEDC	UDC	EUDC
		22°C			-7°C		
HC	g/km	0.071	0.163	0.016	0.234	0.600	0.021
NMHC	g/km	0.066	0.154	0.014	0.218	0.560	0.020
CO	g/km	0.358	0.738	0.136	3.167	8.336	0.147
NO_x	g/km	0.028	0.041	0.021	0.033	0.033	0.034
CO_2	g/km	143.3	181.5	120.9	167.5	219.8	136.9
Fuel Consumption	l/100km	6.2	7.8	5.2	7.4	10.1	5.9
VEHICLE 3							
Emissions	Unit	NEDC	UDC	EUDC	NEDC	UDC	EUDC
		22°C			-7°C		
HC	g/km	0.038	0.096	0.004	0.233	0.623	0.006
NMHC	g/km	0.031	0.080	0.000	0.218	0.585	0.000
CO	g/km	0.327	0.807	0.046	0.883	2.298	0.058
NO_x	g/km	0.022	0.016	0.026	0.181	0.464	0.015
CO_2	g/km	180.2	235.1	148.1	195.5	258.0	159.0

Fuel Consumption	l/100km	7.6	9.9	6.2	8.3	11.0	6.7
VEHICLE 4							
Emissions	**Unit**	**NEDC**	**UDC**	**EUDC**	**NEDC**	**UDC**	**EUDC**
		22°C			**-7°C**		
HC	g/km	0.036	0.094	0.002	0.132	0.356	0.001
NMHC	g/km	0.033	0.090	0.000	0.125	0.339	0.001
CO	g/km	0.344	0.522	0.240	0.708	1.671	0.146
NO_x	g/km	0.015	0.030	0.006	0.033	0.075	0.009
CO_2	g/km	138.2	165.5	122.1	152.5	191.4	129.9
Fuel Consumption	l/100km	5.8	7.0	5.1	6.4	8.2	5.4
VEHICLE 5							
Emissions	**Unit**	**NEDC**	**UDC**	**EUDC**	**NEDC**	**UDC**	**EUDC**
		22°C			**-7°C**		
HC	g/km	0.036	0.093	0.003	0.225	0.607	0.002
NMHC	g/km	0.034	0.088	0.002	0.214	0.579	0.002
CO	g/km	0.239	0.607	0.024	1.189	3.135	0.055
NO_x	g/km	0.007	0.017	0.001	0.004	0.007	0.003
CO_2	g/km	155.9	192.2	134.7	179.3	228.3	150.8
Fuel Consumption	l/100km	6.7	8.3	5.8	7.8	10.1	6.5
PM	mg/km	0.954	-	-	2.038	-	-
PN	#/km	2.14×10^{11}	4.93×10^{11}	5.12×10^{10}	1.54×10^{12}	4.14×10^{12}	3.21×10^{10}
VEHICLE 6							
Emissions	**Unit**	**NEDC**	**UDC**	**EUDC**	**NEDC**	**UDC**	**EUDC**
		22°C			**-7°C**		
HC	g/km	0.033	0.089	0.001	0.212	0.573	0.002
NMHC	g/km	0.031	0.083	0.001	0.203	0.550	0.002
CO	g/km	0.471	0.779	0.293	1.388	3.224	0.326
NO_x	g/km	0.008	0.019	0.001	0.026	0.070	0.001
CO_2	g/km	131.0	155.3	116.8	149.1	182.3	129.9
Fuel Consumption	l/100km	5.5	6.6	4.9	6.3	7.9	5.4

VEHICLE 7							
Emissions	Unit	NEDC	UDC	EUDC	NEDC	UDC	EUDC
		22°C			-7°C		
HC	g/km	0.078	0.201	0.006	0.226	0.598	0.011
NMHC	g/km	0.072	0.185	0.006	0.202	0.534	0.010
CO	g/km	0.554	1.408	0.059	1.749	4.633	0.081
NO_x	g/km	0.036	0.091	0.004	0.051	0.126	0.007
CO_2	g/km	175.8	244.9	135.8	203.4	284.1	156.8
Fuel Consumption	l/100km	7.4	10.4	5.7	8.6	12.3	6.6
PM	mg/km	1.353	-	-	6.830	-	-
PN	#/km	$2.87x10^{12}$	$5.27x10^{12}$	$1.48x10^{12}$	$7.13x10^{12}$	$1.68x10^{13}$	$1.53x10^{12}$

VEHICLE 8 (EU4)							
Emissions	Unit	NEDC	UDC	EUDC	NEDC	UDC	EUDC
		22°C			-7°C		
HC	g/km	0.101	0.274	0.0	0.353	0.957	0.003
NMHC	g/km	0.094	0.257	0.0	0.319	0.865	0.003
CO	g/km	0.402	1.085	0.006	2.457	6.694	0.004
NO_x	g/km	0.009	0.024	0.001	0.075	0.203	0.001
CO_2	g/km	257.8	382.0	185.8	309.3	480.3	210.4
Fuel Consumption	l/100km	10.9	16.2	7.8	13.3	20.8	8.9

VEHICLE 9 (E5)							
Emissions	Unit	NEDC	UDC	EUDC	NEDC	UDC	EUDC
		22°C			-7°C		
HC	g/km	0.049	0.120	0.007	0.358	0.951	0.011
NMHC	g/km	0.043	0.107	0.006	0.329	0.874	0.010
CO	g/km	0.471	1.203	0.042	3.539	9.452	0.078
NO_x	g/km	0.026	0.032	0.023	0.038	0.064	0.023
CO_2	g/km	191.5	250.2	157.1	213.0	271.9	178.5
Fuel Consumption	l/100km	8.3	10.9	6.8	9.4	12.5	7.7
PM	mg/km	0.691	-	-	4.605	-	-

PN	#/km	$2.23x10^{12}$	$4.29x10^{12}$	$1.02x10^{12}$	$4.86x10^{12}$	$1.06x10^{13}$	$1.50x10^{12}$
VEHICLE 9 (E85-E75)							
Emissions	Unit	NEDC	UDC	EUDC	NEDC	UDC	EUDC
		22°C (E85)			-7°C (E75)		
HC	g/km	0.057	0.145	0.005	0.556	1.471	0.021
NMHC	g/km	0.041	0.107	0.003	0.440	1.158	0.019
CO	g/km	0.268	0.660	0.038	3.738	10.045	0.049
NO_x	g/km	0.011	0.019	0.006	0.018	0.032	0.010
CO_2	g/km	180.5	234.5	148.8	207.2	269.0	171.0
Fuel Consumption	l/100km	10.9	14.3	9.0	12.4	16.6	9.9
PM	mg/km	0.406	-	-	0.816	-	-
PN	#/km	$6.67x10^{11}$	$1.13x10^{12}$	$3.94x10^{11}$	$2.28x10^{12}$	$5.63x10^{12}$	$3.24x10^{11}$
VEHICLE 10 (E5) (EU4)							
Emissions	**Unit**	**NEDC**	**UDC**	**EUDC**	**NEDC**	**UDC**	**EUDC**
		22°C			**-7°C**		
HC	g/km	0.073	0.196	0.001	0.238	0.642	0.002
NMHC	g/km	0.068	0.182	0.001	0.223	0.603	0.001
CO	g/km	0.761	1.832	0.135	3.114	8.146	0.182
NO_x	g/km	0.027	0.069	0.003	0.048	0.112	0.011
CO_2	g/km	174.2	242.3	134.4	204.3	291.4	153.6
Fuel Consumption	l/100km	7.5	10.6	5.8	9.0	13.2	6.6
VEHICLE 10 (E85-E75) (EU4)							
Emissions	**Unit**	**NEDC**	**UDC**	**EUDC**	**NEDC**	**UDC**	**EUDC**
		22°C (E85)			**-7°C (E75)**		
HC	g/km	0.068	0.181	0.002	0.361	0.932	0.028
NMHC	g/km	0.056	0.151	0.001	0.273	0.693	0.028
CO	g/km	0.163	0.342	0.059	5.826	15.568	0.141
NO_x	g/km	0.021	0.049	0.005	0.047	0.102	0.015
CO_2	g/km	166.7	234.9	126.8	198.7	283.1	149.4
Fuel Consumption	l/100km	10.1	14.3	7.7	12.1	17.9	8.7

6 CONCLUSIONS

In this report the low temperature emissions of gasoline vehicles (Type VI test) were assessed in view of a possible revision of the relevant emission standards. The current limits are carried over from Euro 3/4 and since then they have never been updated to be consistent with the Type I emission limits set for Euro 5/6 standards. Gaseous emissions at low temperature of flex fuel ethanol vehicles were also investigated in view of the extension of the low ambient temperature test to this category of vehicles.

The main objectives of this study were:

- Analyze the publicly available type approval data to investigate the CO and total HC low temperature emissions of the existing Euro 3/4/5a vehicles.
- Measure low temperature emissions from a range of Euro 5a petrol vehicle/engine technologies, testing various vehicles at the JRC VELA Laboratory. Two flex fuel ethanol vehicles (one Euro 4 and one late technology Euro 5) were also included in the measurement matrix, which were tested running in two fuels, with low and high ethanol content.

The type approval data published by the Kraftfahrt-Bundesamt (KBA) contains the low temperature emissions of gasoline vehicles certified according to different emission standards. The analysed data covers models available on the European market up to the year 2009 and refer to Euro 3/4/5a emission level vehicles. In order to investigate the evolution of the low temperature performances, the engines were divided into sub-categories corresponding to the different emission levels (Euro 3, 4 and 5a) and to the different fuel injection technologies or the kind of fuel used in case of bi-fuel engine. From the analysis of the type approval data the following conclusions can be drawn:

- ➢ 90% of all the petrol engine models included in the KBA data set, regardless of their emission level or engine technology, emit less than 7.7 g/km of CO or 1.47 g/km of total HC (emissions measured over the UDC driving cycle at -7°C). These values have to be compared to the current legislative limits which are 15 g/km and 1.8 g/km for CO and total HC respectively. 70% of all the petrol engines emitted less than 5.1 g/km of CO or 1.17 g/km of total HC in Type VI test.
- ➢ 90% of the Euro 5a petrol engine models included in the KBA data set emit less than 5.6 g/km of CO or 1.43 g/km of total HC in the Type VI test, while the respective values for the 70th percentile were 3.8 g/km and 1.16 g/km respectively. The percentage of Euro 5a engines that emitted simultaneously less than 5.6 g/km of CO and 1.43 g/km of total HC was 81.5%.
- ➢ In general, vehicles equipped with direct injection engines seem to have lower CO and HC emissions in the Type VI test than vehicles with port fuel injection engines.
- ➢ The transition from the Euro 3 to the stricter Euro 4 emission limits for the Type I test, resulted in greatly improved performances of emission control devices. This improvement affected also the emission performances at low temperature as demonstrated by the emission levels of Euro 4 vehicles measured in the Type VI test compared to Euro 3 vehicles. The introduction of the Euro 5a emissions standards seems to have led to a smaller improvement of the low temperature emission

performances. This is probably due to the fact that there is no further reduction of the CO and HC emission standards passing from Euro 4 to Euro 5a.

The JRC measured the emissions of seven Euro 5a and one Euro 4 mono fuel gasoline vehicles at 22°C and -7°C (Type I and Type VI test). Of the tested vehicles, the majority was equipped with port fuel injection engines and three cars were equipped with direct injection engines. In addition to the regulated emissions (CO and total HC), NO_x emissions were also measured in the low temperature test. All the tested mono fuel vehicles resulted to be compliant with the legislative limits of Type VI test.

- In general, CO and HC emissions increased remarkably at -7°C. Despite this large increase, all the tested mono fuel Euro 5a vehicles exhibited emissions lower than 8.3 g/km for CO and 0.62 g/km for total HC. These values are well below the current legislative limits. Excluding the vehicle that exhibited the highest CO emissions in the Type VI test (Vehicle 2), all the other vehicles had emissions lower than the 90^{th} percentile of Euro 5a vehicles available type approval data (5.6 g/km for CO or 1.43 g/km for total HC).
- The Euro 4 mono fuel vehicle emitted 6.7 g/km for CO and 0.96 g/km for total HC over the UDC cycle at -7°C (Type VI test). These values were below the legislative limits. However, the performance of the specific vehicle may not be representative for all Euro 4 compliant vehicles, since only one Euro 4 mono-fuel vehicle has been tested.
- Two flex fuel ethanol vehicles were tested in both Type I and Type VI tests, one certified as Euro 4 and one late technology direct injection turbocharged Euro 5a. At 22°C the gaseous emissions decreased when the vehicles ran on the high ethanol content fuel. At -7°C the first vehicle did not comply with the current Type VI limits for CO with high ethanol content fuel. Euro 5a FFV performed better, but in general, CO and HC emission performance of this flex fuel vehicle was inferior compared to the majority of the tested mono fuel vehicles, especially in the Type VI test regardless of the used fuel.
- NO_x emissions were also measured in the low temperature test although these are not currently regulated. For the majority of the mono-fuel Euro 5a compliant vehicles NO_x emissions measured at -7°C over the NEDC cycle increased and resulted to be up to 3.5 times as the emissions levels measured at 22°C. The only exceptions were Vehicle 5 that turned out to have lower NO_x emissions at -7°C than at 22°C and Vehicle 3 that exhibited almost 8 times more NO_x at -7°C than at 22°C. This seems to take place due to a very peculiar combustion strategy adopted in the first seconds of the cycle. All the other tested vehicles emitted less than 0.126 g/km of NO_x at -7°C over the UDC cycle. The respective value for Vehicle 3 was 0.464 g/km.
- Euro 4 mono fuel vehicle emitted 0.203 g/km and 0.075 g/km of NO_x over the UDC and NEDC cycle at -7°C. These values were 8 times increased compared to the respective results at 22°C.
- Finally, particulate emissions in terms of mass and number were also discussed for two of the tested vehicles. One of the two vehicles was equipped with a direct injection engine (G-DI) running in lean mode, while the other with a conventional port fuel injection engine (PFI). As far as the PFI vehicle is concerned, the particles were mainly emitted during the cold start – warming phase of the engine and in the low temperature test the particle number increased significantly (one order of magnitude higher). On the contrary, in the case of the G-DI vehicle the particles were emitted continuously over the whole NEDC cycle and both the mass and number turned out to be almost

independent on the test temperature. However this vehicle exceeded the Euro 5b particle number limit for diesel vehicles by two orders of magnitude.

7 LIST OF SPECIAL TERMS AND ABBREVIATIONS

CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CVS	Constant Volume Sampler
DPF	Diesel Particulate Filter
EC	European Commission
UDC	Urban Driving Cycle (Part 1 of the NEDC driving cycle)
EGR	Exhaust Gas Recirculation
EUDC	Extra-Urban Driving Cycle (Part 2 of the NEDC driving cycle)
Euro # / EU#	European Emission Standard
FFV	Flex Fuel Vehicles
FTP-75	Federal Test Procedure
G-DI	Gasoline Direct Injection
HC	Hydrocarbon
JRC	Joint Research Centre
KBA	Kraftfahrt –Bundesamt (Germany’s Federal Motor Transport Authority)
LPG	Liquefied Petroleum Gas
NEDC	New European Driving Cycle
NMHC	Non Methane Hydrocarbons
NO_x	Oxides of Nitrogen (NO & NO_2)
O_2	Oxygen
PFI	Port Fuel Injection
PM	Particulate Matter
PN	Particle Number
RG	Petrol or Electrical

US	United States
VELA	Vehicle and Engine Emission Laboratories
WG	Petrol Walkel Rotary

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Abstract
The Commission Regulations (EC) No 692/2008 and 715/2007 set the regulatory framework for type approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5/6. In particular these regulations set the emission standards and the related implementing measures, divided into three different steps, that will enter into force between 2009 (Euro 5) and 2014 (Euro 6). However the above mentioned Regulations leave open some issues regarding the Euro 5b and the Euro 6 emission standards to be addressed and defined before the entry into force of these pieces of legislation. As far as the low temperature emission test for gasoline vehicles is concerned the current emission limits, carried over from Euro 3/4, are no longer appropriate for vehicles meeting the Euro 5/6 emission standards.
This report provides a picture of the low temperature emission performances (based on type approval data of Type VI test) of the current generation of gasoline vehicles. It also summarizes the main results of the experimental activity carried out at JRC to investigate the behaviour at low temperature of Euro 5 passenger cars and provide useful data for the revision of the low temperature emission standards for gasoline vehicles. Moreover, the analysis includes also results of Ethanol Flex Fuel Vehicles in view of the extension of the low temperature test to this category of vehicles.

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